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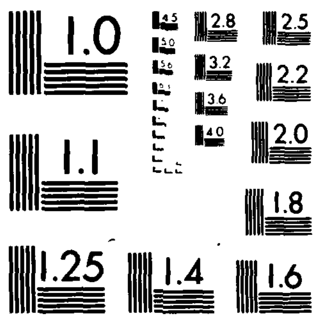


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# FEASIBILITY EVALUATION OF ADVANCED MULTIFREQUENCY EDDY CURRENT TECHNOLOGY FOR USE IN NAVAL AIR MAINTENANCE ENVIRONMENT


Handling and Servicing/Armament Division
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733


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# FEASIBILITY EVALUATION OF ADVANCED MULTIFREQUENCY EDDY CURRENT TECHNOLOGY FOR USE IN NAVAL AIR MAINTENANCE ENVIRONMENT


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The optimization of a multifrequency eddy current test was performed for the detection and characterization of second-member corrosion using computer programs. The results of the analytical studies showed that both inner and outer surface corrosion could be detected and quantified. Air gap variations could also be distinguished from corrosion using multifrequency data. These results were confirmed experimentally using phase-sensitive eddy current instrumentation.

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## SUMMARY AND CONCLUSIONS

Initial studies conducted by Battelle-Columbus Laboratories, reference (a), identified potential advantages in using more advanced eddy current techniques in Naval Air Systems Command maintenance inspection applications. Recommendations were made for a follow-on effort in which an existing inspection problem would be addressed using multifrequency approaches.

Messrs. Eli Nicosia and Richard McSwain at the Naval Air Rework Facility (NAVAIREWORKFAC), Pensacola, were contacted by Mr. Richard Deitrich of the Naval Air Engineering Center, and a candidate problem was identified to be the detection and characterization of corrosion between the T-39 fuselage skin (first member) and the airframe (longerons and ribs - second member). Present NAVAIREWORKFAC Pensacola eddy current inspection techniques rely on the use of a relatively high inspection frequency for the detection of second-member outer surface corrosion, that is outboard surface corrosion. This is accomplished by detecting the presence of a gap which is created between the aircraft skin/structural member as a result of corrosion product expansion. Variations in skin/structural spacing can occur without the presence of corrosion, resulting in the potential for incorrect calls. In addition, second-member inner surface corrosion, that is inboard surface corrosion, cannot be detected using present techniques.

The objective of the present effort was to implement multifrequency techniques with the specific goals of:

1. Detecting corrosion on the inner surface of the second member,

2. Quantifying inner surface and outer surface second-member corrosion depth, and

3. Differentiating between inner surface corrosion and the normally occurring air gap.

The optimization of a multifrequency eddy current method for the detection and characterization of second-member inner and outer surface corrosion was modeled using a computer program originally developed by C. V. Dodd at Oak Ridge National Laboratory. Refinements were made to the program for increased computational efficiency. The results of the analytical studies showed that inner surface and outer surface corrosion could be detected and quantified with regards to depth. Air-gap variations could also be distinguished using multifrequency eddy current data. The analytical results were confirmed experimentally using phase-sensitive eddy current design. Optimization of the overall eddy current test design was greatly aided by the use of the modified computer program.

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Ref: (a) NAVAIRENGCEN Report NAEC-92-128 of 28 Sep 1978: Feasibility Evaluation of Advanced Eddy Current Inspection Equipment For Use in Naval Aviation Maintenance Environment

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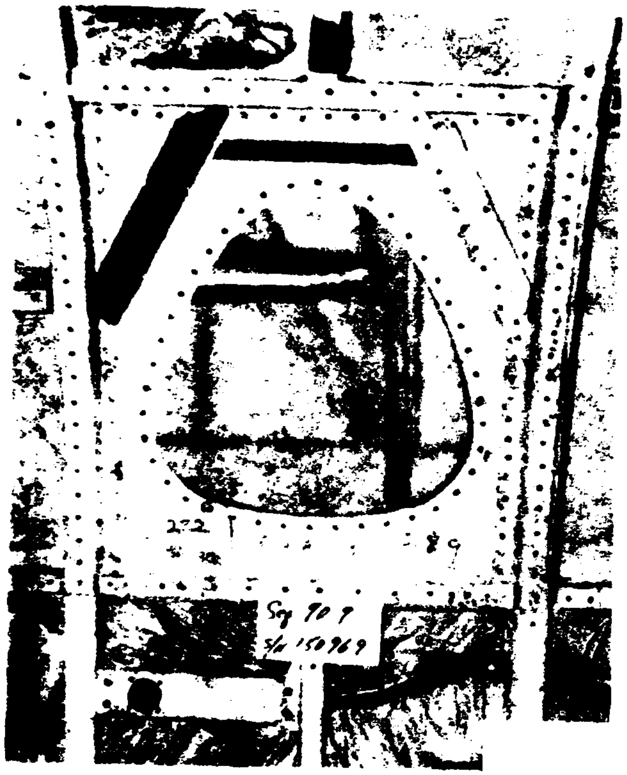
# I. INTRODUCTION

## A. GENERAL.

1. The objective of this program was to demonstrate the benefits of multifrequency eddy current technology as applied to a particular Naval Air Systems Command (NAVAIRSYSCOM) maintenance inspection problem--the detection and characterization of corrosion hidden beneath the T-39 aircraft skin surfaces. Corrosion presently initiates on the aircraft structural member at either the inner or outer surface. Inner surface structural corrosion (ISSC) is presently undetectable using existing NAVAIRSYSCOM maintenance inspection procedures. Outer surface structural corrosion (OSSC) product, if severe, forces a separation between the two members. Existing NAVAIRSYSCOM maintenance inspection methods rely on the use of an eddy current technique for the detection of this skin/structure air gap. The gap magnitude is indicative of corrosion severity. Variation in skin/structure spacing can occur without any structural corrosion being present. Hence regions which do not exhibit any corrosion can be incorrectly identified as being corroded. Figure 1 illustrates T-39 ISSC and OSSC as they typically occur.

2. In order to systematically investigate the overall problem of the detection and characterization of aircraft structural member corrosion, computer programs developed by C. V. Dodd at Oak Ridge National Laboratory were utilized. These programs were modified for increased computational efficiency and were used to study two important eddy current test parameters which are coil excitation frequency and coil size. ISSC and OSSC were modeled as extended areas of change in overall skin/structural member thickness. The effects of air-gap variations between the skin and structural member were handled analytically by considering a three-layer model of the aircraft skin and structural member where the spacing between the two is variable. The results of the computer studies suggest that a two-frequency multifrequency system can detect and characterize ISSC and OSSC as well as distinguish between air-gap variations. The analytical results were confirmed experimentally using simulated sections of corroded panels. Phase-sensitive eddy current instrumentation incorporating reflection coils was used for data acquisition.




Backside of T-39 Window Showing
Inner Surface Structure Corrosion

Areas of Outer Surface Structural Corrosion
on an Extruded Longeron

FIGURE 1. EXAMPLES OF INNER SURFACE AND OUTER SURFACE STRUCTURAL CORROSION

# II. REFLECTION COIL INSTRUMENTATION

## A. COILS.

1. Phase-sensitive eddy current instrumentation incorporating reflection coils was utilized throughout the course of this program. Features of this type of instrumentation are described and compared with the more conventional eddy current instrumentation.

B. COIL TYPES. The most common type of coil used in conventional eddy current testing is the parametric coil. A parametric coil is defined as any coil in which the eddy current generator (drive coil) is the same as the detector (pickup coil). An alternate type, in which the drive and pickup coils are physically separated, is called a transformer coil. The voltage detected by the eddy current instrument is induced in the pickup coil by transformer-like action, that is through mutual inductance effects.

1. The use of transformer coils offers two primary advantages over parametric coils. The first advantage is the simplification of the associated electronic circuitry afforded by the isolation of the power driving circuits and the measuring circuits. Secondly, it is very difficult to isolate variations in the intrinsic impedance ($R + j\omega L$) of parametric coils from variations of the coil impedance due to the variation of test parameters such as thickness, conductivity, or the presence of discontinuities.

2. Variations in coil resistance with temperature are especially difficult to eliminate, and may cause drastic errors in the eddy current measurements. Transformer coils, in principle, can be made free of this effect if the drive coil is driven with a constant current source, and pickup coil voltage is measured with a high impedance vector voltmeter. Simplicity of design, though, is a considerable advantage of parametric coils over transformer coils, as will be shown below.

3. The main contributor to the design and use of transformer coils in this country has been C. V. Dodd at the Oak Ridge National Laboratory. His design of a transformer coil, which he calls a reflection coil, is shown in Figure 2. As can be seen, it consists of a large drive coil surrounding two smaller pickup coils. The pickup coils are connected in series opposition so that the voltage induced in the secondary windings away from any material is zero, and the voltage across the secondary is due only to the electromagnetic and dimensional properties of the material being tested.

4. Reflection coils may be characterized by several sets of parameters. These are:

   a. dimension of the drive coil ($r_1$, $r_2$, $\ell_1$; 3 parameters)

   b. dimensions of the pickup coils ($r_3$, $r_4$, $\ell_3$; 3 parameters)

   c. location of the pickup coils with respect to the drive coil ($\ell_5$; 1 parameter)

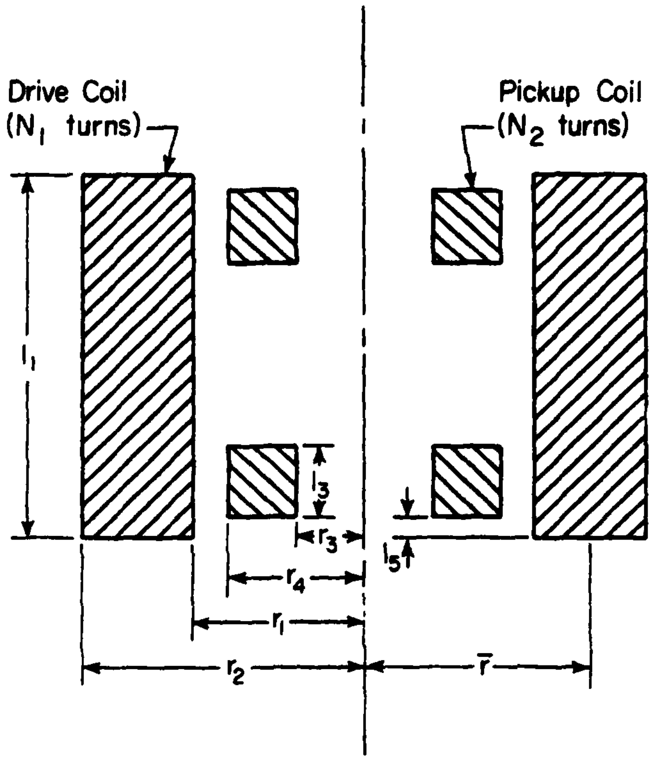



FIGURE 2. CROSS-SECTIONAL VIEW OF A REFLECTION COIL

d. electromagnetic character of drive coil (number of winding turns, $N_1$; 1 parameter)

e. electromagnetic character of pickup coils (number of winding turns, $N_2$; 1 parameter)

Thus, there are nine different parameters that control the design of reflection coils, all of which may be varied more or less independently. Compare this with a parametric coil, which has four parameters (three dimensional and one electromagnetic), and it can be seen that parametric coils are, by far, simpler to design.

5. Fortunately, Dodd, who promulgated the use of reflection coils, has also done a great deal to simplify their design. He has examined, in detail, the interdependency of the various parameters to come up with one basic design which depends most strongly on only one parameter, the drive coil mean radius, denoted as $\bar{r}$ in Figure 2. In general, smaller coils are used for low penetration, high frequency, and high resolution, and large coils are for deep penetration, low frequency, and reduced resolution.

C. PHASE-SENSITIVE DETECTION. Reflection coils are typically used with phase-sensitive detection schemes. Advantages and disadvantages of this approach are now considered.

1. Any sinusoid can be characterized by three parameters, one of which is frequency. The other two parameters are the magnitude of the signal and its phase lead or lag relative to some reference voltage. These will be called A and $\phi$ respectively. These two parameters may, in turn, be related to two others, commonly called the inphase and quadrature, designated x and y respectively. The transformation between these two sets of parameters is given by

$$\begin{aligned} x &= A \cos \phi \\ y &= A \sin \phi \\ \phi &= \tan^{-1}\left(\frac{y}{x}\right) \\ A &= (x^2 + y^2)^{1/2} \end{aligned} \tag{1}$$

Detection schemes may be devised which measure either of the two sets. These measurements are usually made independently of each other, though, since the electronic circuitry necessary for the above transformation is more complex than the circuitry which measures either set. Circuits which measure $\phi$ are called phase-sensitive instruments, and those which measure x and y are called vector voltmeters. Measurements of the magnitude A are rather trivial, and will not be discussed.

2. Since there are two sets of parameters which describe the eddy current response, the question arises as to which should be used. The answer to this question depends not only on the material parameter being measured, but also on whether the eddy current system being used balances out certain constant (or almost constant) voltages which appear across the pickup coil.

3. The voltage across the pickup can be separated into two parts, as illustrated in Figure 3: the voltage due to the mutual inductance between the drive and pickup coil (self-inductance in parametric coils) and the voltage due to the presence of the test material. All systems provide a means of nulling or balancing out the first of these two voltages; some internally through a balance network, and some externally through the coil configuration. Typically, parametric coils are balanced internally and transformer coils externally, though this is not necessarily so.

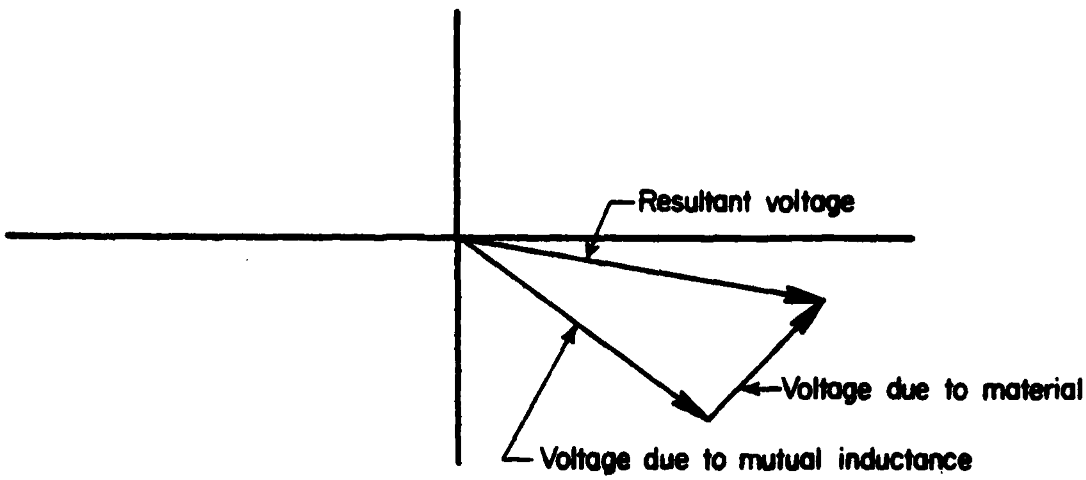
4. The remaining voltage, then, is due to the presence of the material and is determined by the bulk material properties (resistivity, conductivity, and geometry). This, too, can be divided into two parts: one due to the nominal material properties, and the other due to a change in one or more of these properties. This is illustrated in Figure 4, where the sinusoid due to the nominal material characteristics is the vector A, and that due to a change is the vector B. In an unbalanced system, the two add, giving a resultant vector A. In a balanced system, A is eliminated, leaving B. In general, phase-sensitive instruments do not allow this kind of balancing, while vector-voltmeter-based systems do.

5. The output of a phase-sensitive detector is a dc voltage proportional to $\phi$, so it is limited to something corresponding to ± 180°, which means that 0.02° is about 1 millivolt on a ± 10-volt full scale range. Phase measurements, then, have a limited dynamic range regardless of the amplitude of the sinusoid being measured. However, they also have a limited sensitivity. It is not difficult to show that the change in phase angle $\Delta\phi$, due to the presence of the vector B, is

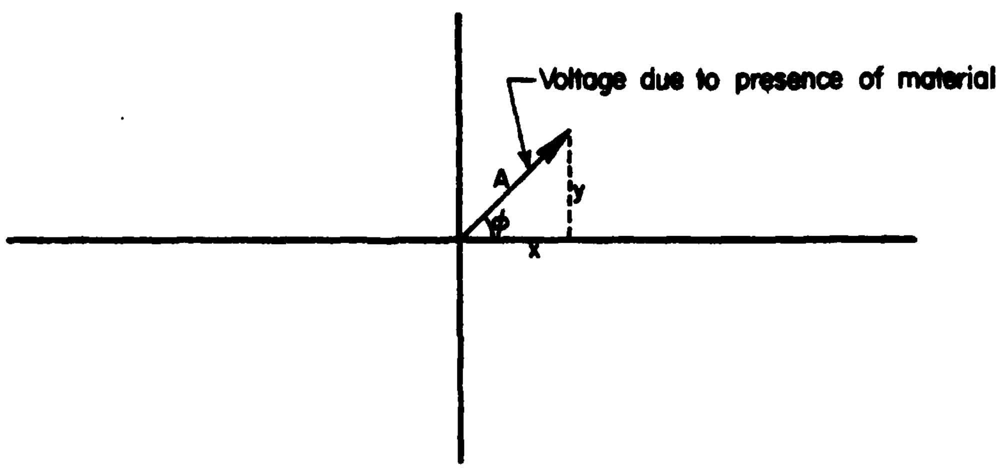
$$\Delta\phi = \tan^{-1}\left(\frac{\sin\theta}{\frac{A}{B} + \cos\theta}\right) \qquad (2)$$

where A, B, $\theta$, and $\Delta\phi$ are defined in Figure 4. A/B ratios of a thousand or more are not unrealistic, which means that $\Delta\phi$ is limited to ± 0.06°, depending on $\theta$ . On the other hand, phase-sensitive instruments can be made more insensitive to liftoff variations than can vector-voltmeters, though a demonstration of this is beyond the scope of this discussion.

6. The conclusion is that phase-sensitive detectors and vector voltmeters are both useful under different test situations. Phase-sensitive instruments are good for measuring bulk properties, surface and slightly subsurface defects where A/B is smaller, and when sensitivity to liftoff is of concern. Vector-voltmeters, on the other hand, are best for detecting the smaller volume flaws and flaws further into the material where A/B is large. There is, of course, no well defined delineation between the two, and there is much overlap in their useful test applications.

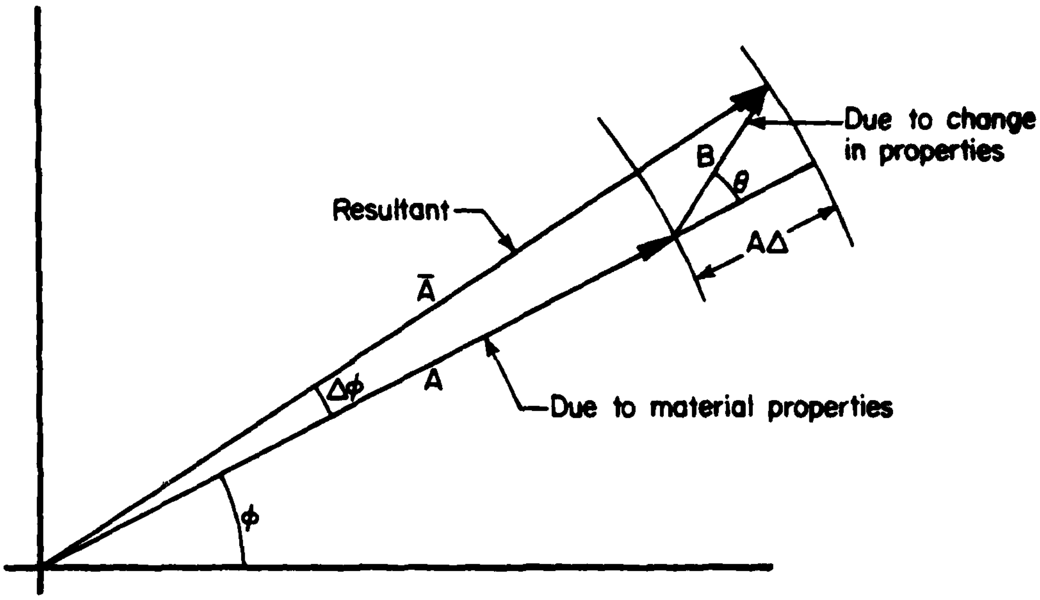



a) Before mutual inductance is balanced out

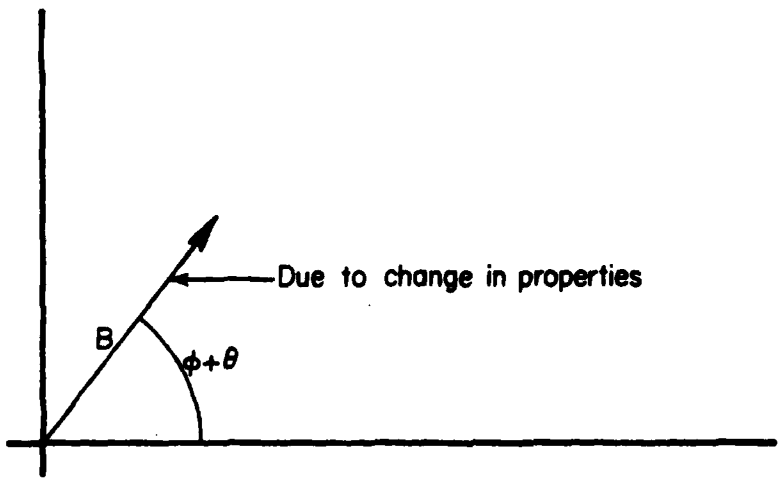



b) After mutual inductance is balanced out

FIGURE 3. VECTOR REPRESENTATION OF MUTUAL INDUCTANCE VOLTAGE ACROSS AN EDDY CURRENT COIL




a) In an unbalanced system




b) In a balanced system

FIGURE 4. VECTOR REPRESENTATION OF VOLTAGE DUE TO A TEST ARTICLE NEAR AN EDDY CURRENT COIL

# III. EDDY CURRENT TEST OPTIMIZATION USING COMPUTER MODELING

## A. INITIAL CONDITIONS.

1. The computer program used to model the airframe corrosion problem is a modified version of C. V. Dodd's program MULTIT. The modifications were made to simplify the data input routines, and to decrease the execution time of the integration subroutines by approximately 15 percent. The program is designed to analyze thickness changes in any given layer in a multilayer conducting medium.

2. As shown in the previous section, Dodd has eliminated much of the tedium in designing reflection coils, channeling the present effort into selecting only two test parameters, the coil mean radius and the test frequency. These are determined solely by the dimensional and electromagnetic properties of the test samples under consideration.

3. In general, there are two parameters which characterize any layer of the multilayer system (assuming that all layers are nonmagnetic); these are thickness and conductivity. Since the materials under consideration may be divided into three parts (that is the skin, the structural member, and the sealant/air gap* or corrosion products between the two), there are six parameter variations which should be investigated to completely describe the given problem. Actually there are only five, since the conductivity of air, sealant, and corrosion products is zero, for all practical purposes. A proper investigation of all permissible variations was beyond the scope of this project; hence, only certain variations were allowed, which, it was thought, would indicate the method of solution necessary for any variation of the above parameters.

4. The following assumptions were made:

   a. The thickness of the skin was 0.050 inch, and did not vary.

   b. The thickness of the structural member was 0.250 inch, and did not vary, except when corrosion was present.

   c. The resistivity of the skin was the same as that of the structural member, neither of which varied. This resistivity was set at 5.0 ohm-cm, a nominal value for aluminum.

   d. Corrosion of the structural member at the faying surface effectively increased the thickness of the air or sealant gap by the thickness of the corrosion products, while decreasing the thickness of the structural member by the same amount.

---

* The terms sealant thickness and air-gap thickness are used interchangeably, since, from an eddy current testing standpoint, they are equivalent.

e. Corrosion of the structural member on the side away from the faying surface decreased the thickness of the structural member, but did not change the thickness of the air or sealant gap.

5. During the course of this project, ten cases were analyzed, as detailed in Table I. OSSC, outer surface corrosion, is taken to be at the structural member faying surface; and ISSC, inner surface corrosion, refers to corrosion of the structural member away from the faying surface. These ten cases can be divided into four categories:

a. The nominal structure (case 1)

b. Corrosion on the inner surface of the structural member (cases 2, 3, and 4)

c. Corrosion on the outer surface of the structural member (cases 5, 6, and 7)

d. Changes to the sealant or air gap, an extraneous variable (cases 8, 9, 10).

A pictorial representation of the four categories is shown in Figure 5.

TABLE 1. GEOMETRIES OF THE COMPUTER-ANALYZED CASES

| Case | Thickness (In.) Member | Sealant | Skin | Defect Type |
|---|---|---|---|---|
| 1 | 0.250 | 0.005 | 0.050 | Nominal Structure |
| 2 | 0.2375 | 0.005 | 0.050 | 5% Corrosion - ISSC |
| 3 | 0.225 | 0.005 | 0.050 | 10% Corrosion - ISSC |
| 4 | 0.200 | 0.005 | 0.050 | 20% Corrosion - ISSC |
| 5 | 0.2375 | 0.175 | 0.050 | 5% Corrosion - OSSC |
| 6 | 0.225 | 0.030 | 0.050 | 10% Corrosion - OSSC |
| 7 | 0.200 | 0.055 | 0.050 | 20% Corrosion - OSSC |
| | | | | Sealant Thickness Change Equivalent To: |
| 8 | 0.250 | 0.175 | 0.050 | 5% Corrosion |
| 9 | 0.250 | 0.030 | 0.050 | 10% Corrosion |
| 10 | 0.250 | 0.055 | 0.050 | 20% Corrosion |

6. Existing computer models, including the one used here, have certain limitations on the size of modeled defects, such as corrosion, due to the mathematical complexity of modeling electromagnetic phenomena. Presently, flaw sizes must be limited to either very large volume or very small volume, as related to the size of the inspection coil. Large volume analysis was selected in this

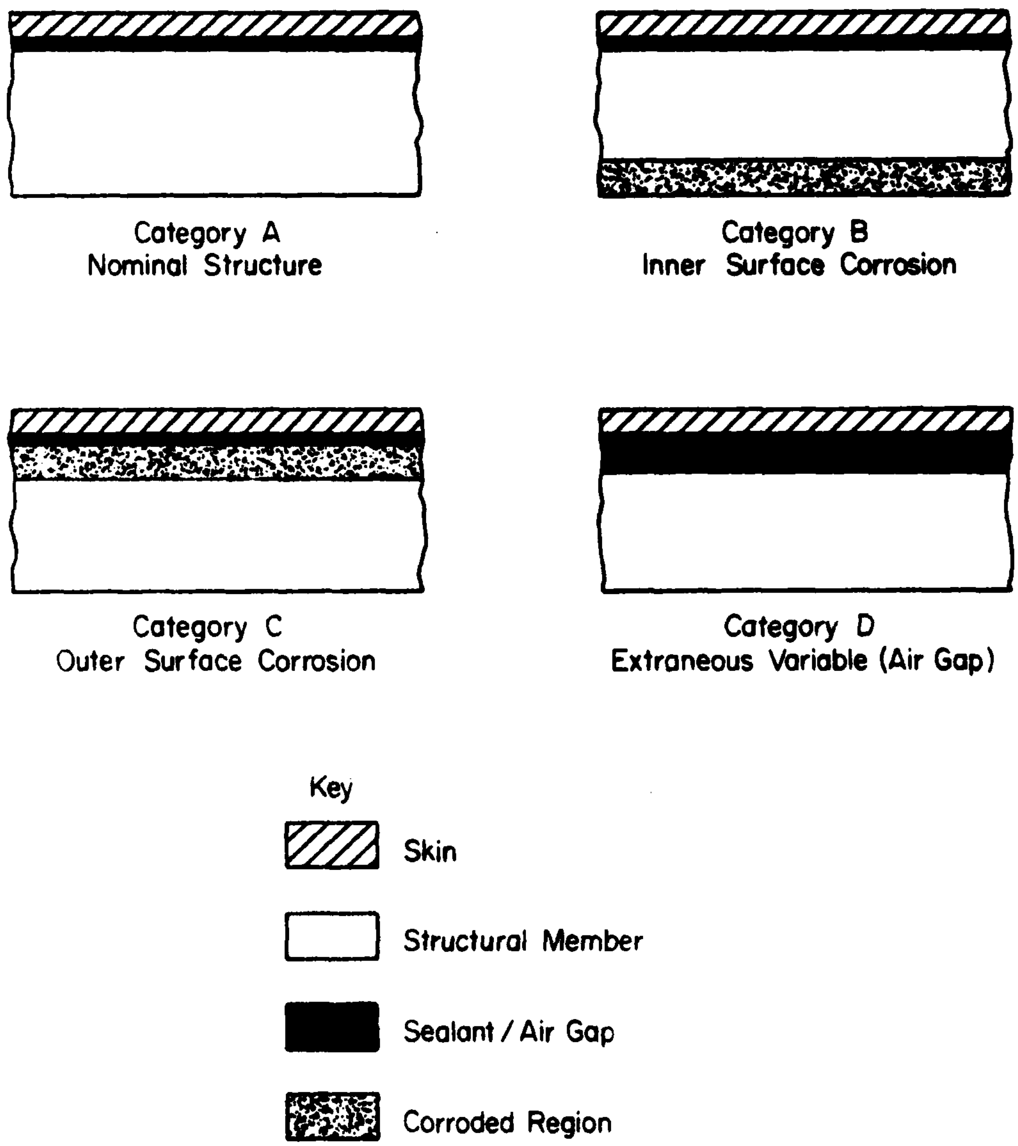



FIGURE 5. PICTORIAL REPRESENTATION OF THE VARIOUS CORROSION CATEGORIES

project, and it was assumed that the trends predicted by the large volume analysis would accurately follow the trends of intermediate-sized flaws. For the most part, this assumption was shown to be true.

B. RESULTS OF THE ANALYTIC STUDIES. This section contains the results of the computer modeling for the various categories detailed in the previous section. In particular, it is shown how extraneous variables, such as changes in the air-gap thickness, may be discriminated from corrosion at the outer surface by using multiple inspection frequencies.

1. DETECTION AND CHARACTERIZATION OF CORROSION - ISSC.

a. Cases 2, 3, and 4 of category B were examined to determine the relationship between eddy current phase angle and test frequency for different depths of corrosion. The results of the computer analysis are shown in Figure 6. Only one coil was analyzed for this case, the 300A, at frequencies ranging from 100 Hz to 1000 Hz. The various corrosion depths are indicated as a percentage of the structural member thickness. The trends to be noted from these results are:

(1) As frequency decreases, sensitivity increases, then decreases, indicating a point of maximum sensitivity at about 200 Hz.

(2) Phase roll-off with frequency appears to drop faster at the high frequencies than the low; that is, it is better to be below the maximum than above it.

(3) The frequency chosen for this coil appears to relate well with skin depth $\delta$, since $\delta$ at 200 Hz is about 0.31 inch.

b. In most eddy current testing, it is as important to characterize flaws as it is to detect them; in this case, one should be able to give a figure for the remaining thickness after corrosion. Apparently this is possible, since there is a monotonically increasing relationship between phase angle and corrosion depth (see Figure 7). However, it must be remembered that this derived relationship is for large volume flaws, and that smaller volume flaws will give smaller phase angles, at the same depth, than large volume flaws. Thus, any practical calibration curves must measure phase angles for corroded regions of different areas as well as different depths.

c. Phase angle, rather than magnitude of the eddy current signal, is used as the discriminating signal for two reasons. First, it is directly relatable to the thickness of the test piece, and second, it can be made relatively insensitive to liftoff effect, depending on the coil size, frequency, and instrumentation used. The magnitude of the eddy current signal, on the other hand, is almost directly proportional to liftoff, and cannot be compensated for liftoff variations.

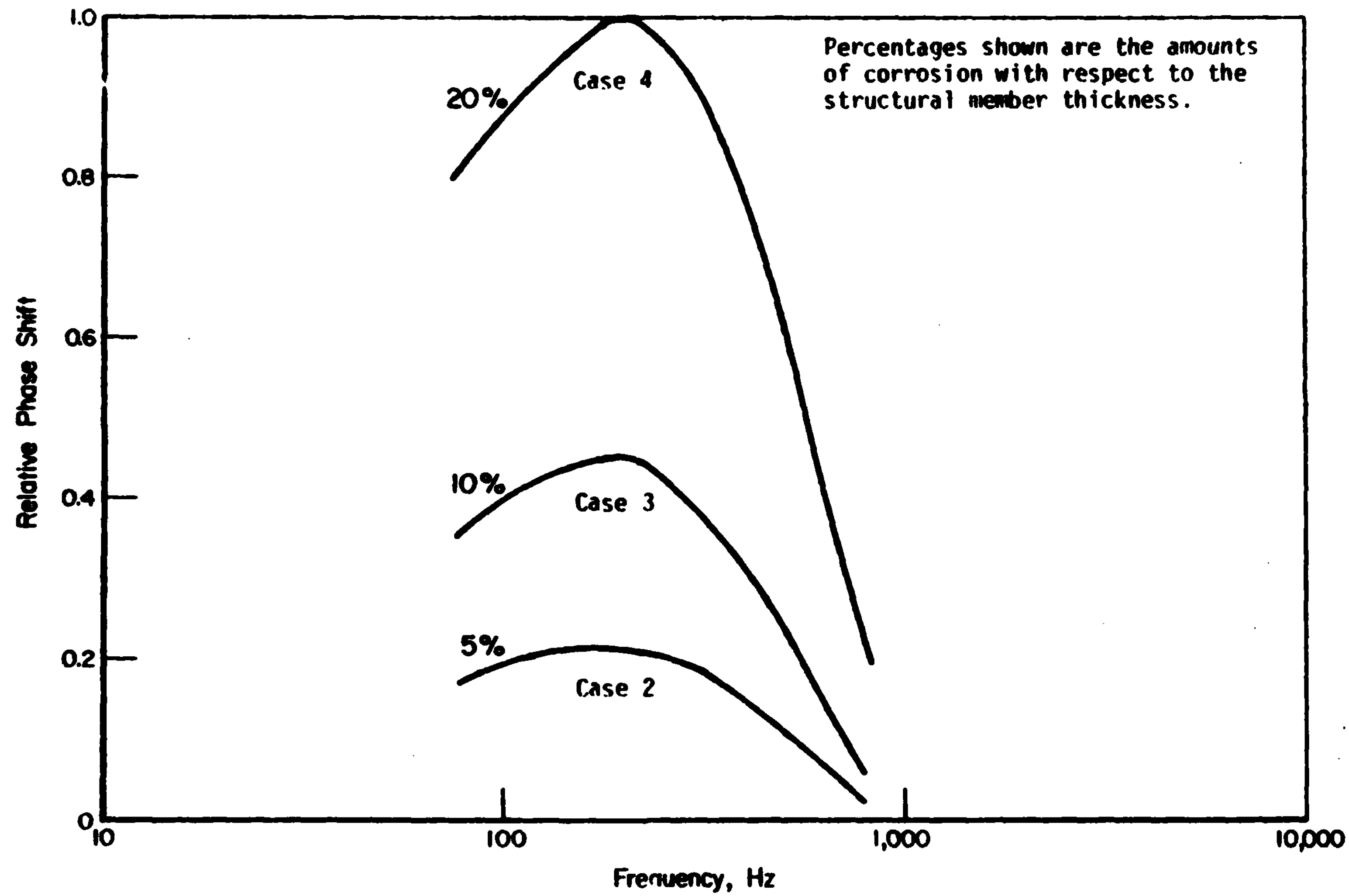



FIGURE 6. DEFECT SENSITIVITY FACTOR VERSUS FREQUENCY FOR INNER SURFACE CORROSION (300A COIL)

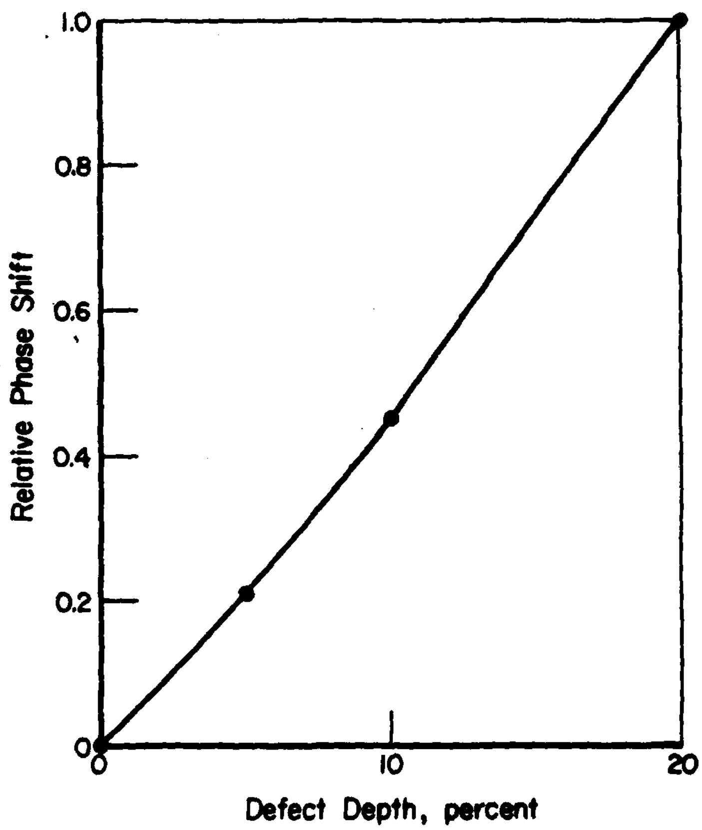



FIGURE 7. EDDY CURRENT PHASE ANGLE VERSUS DEFECT DEPTH (200 Hz)

2. <u>DETECTION AND CHARACTERIZATION OF CORROSION - OSSC.</u> Cases 5, 6 and 7 of category C (refer to Figure 5) were examined to determine the relationship between eddy current phase angle and test frequency for different depths of corrosion on the outer surface of the structural member. Two coils were used in this analysis: the 300A at frequencies ranging from 100 Hz to 5 kHz, and the 150A at frequencies ranging from 100 Hz to 10 kHz. The resulting data for the 300A is shown in Figure 8, and that for the 150A is shown in Figure 9. The trends to be noted are:

a. As frequency decreases, the sensitivity increases then decreases, pointing out a region of maximum sensitivity at about 2 kHz, for both coils.

b. Again, phase rolloff is higher for higher frequencies, indicating that it is better to be too low in frequency than too high.

c. Optimum test frequency correlates well with skin depth $\delta$ since $\delta$ at 2 kHz = 0.10 inch, just over the thickness of the aircraft skin.

Again, it appears that flaw characterization, as well as detection, is possible as long as flaw area is taken into account. Computer-generated calibration curves for both coils are shown in Figure 10.

3. <u>DETECTION AND CHARACTERIZATION OF SEALANT THICKNESS CHANGES.</u> The primary detection mechanism of OSSC is through the separation of the skin from noncorroded metal of the structural member. Obviously, then, any phenomena which causes a change in this separation will be interpreted as OSSC, even though it may not be. Naturally occurring changes in the sealant or air-gap thickness must somehow be discriminated against. To do this, cases 8, 9, and 10 of category D were analyzed with the computer modeling programs, using both the 300A and 150A coils, at frequencies ranging from 100 Hz to 10 kHz. The resulting phase angle change versus frequency, with air-gap thickness as a parameter, are superimposed on the previous Figures 8 and 9 in Figures 11 and 12. The important points to note are listed below:

a. At high frequency (above 1 kHz), there is essentially no difference between equivalent sealant thickness changes and corrosion of the outer surface.

b. As frequency decreases, the phase-angle rolloff for sealant thickness changes is larger than for equivalent corrosion of the outer surface, thus allowing discrimination between sealant thickness changes and corrosion.

c. The rolloff is larger for the larger coil, indicating that such discrimination could be more easily performed with the 300A than the 150A. This is due to the decreased penetration capabilities of smaller coils.

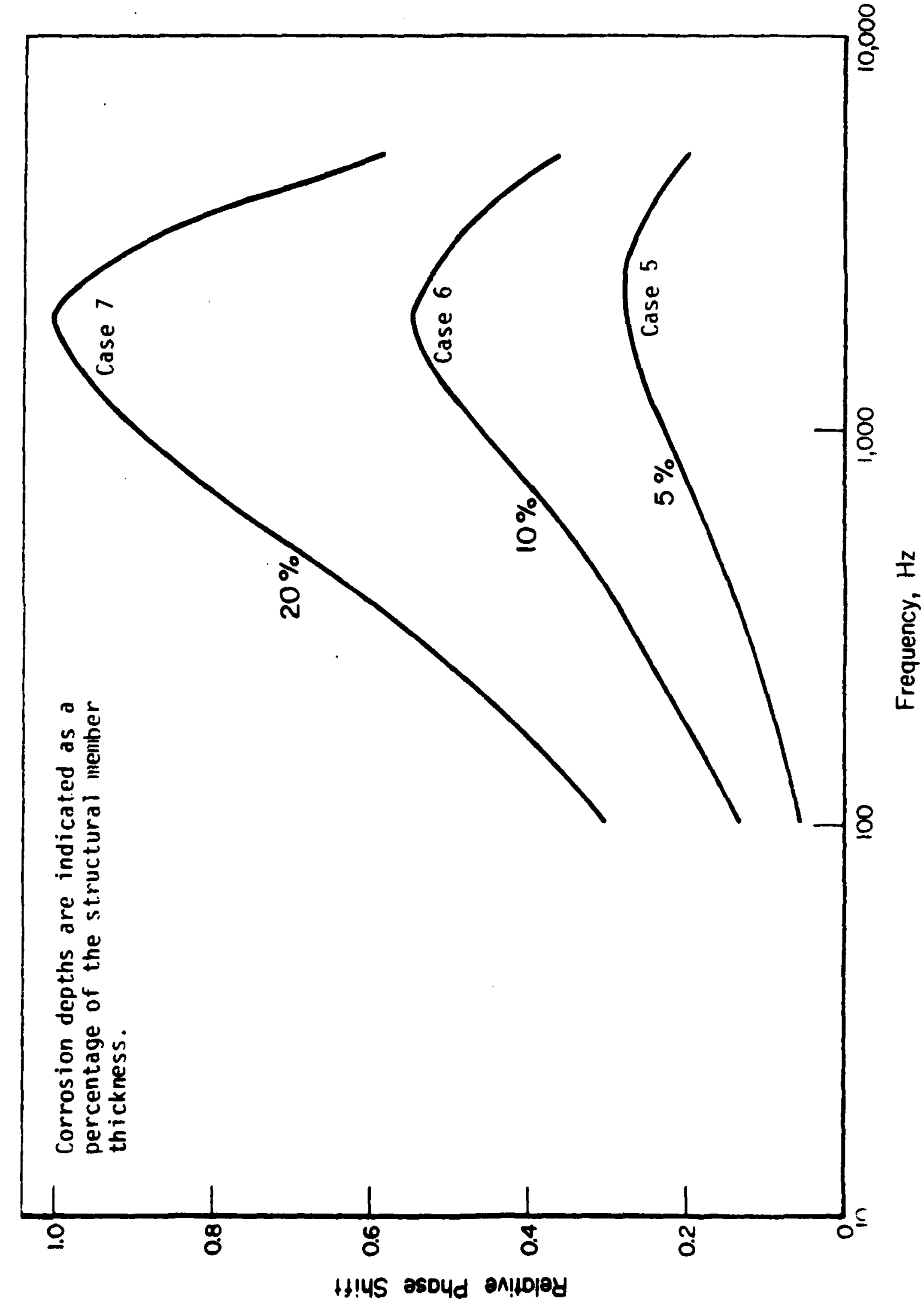



FIGURE 8. OUTER SURFACE DEFECT SENSITIVITY FACTOR VERSUS TEST FREQUENCY FOR DIFFERENT CORROSION DEPTHS (300A COIL)

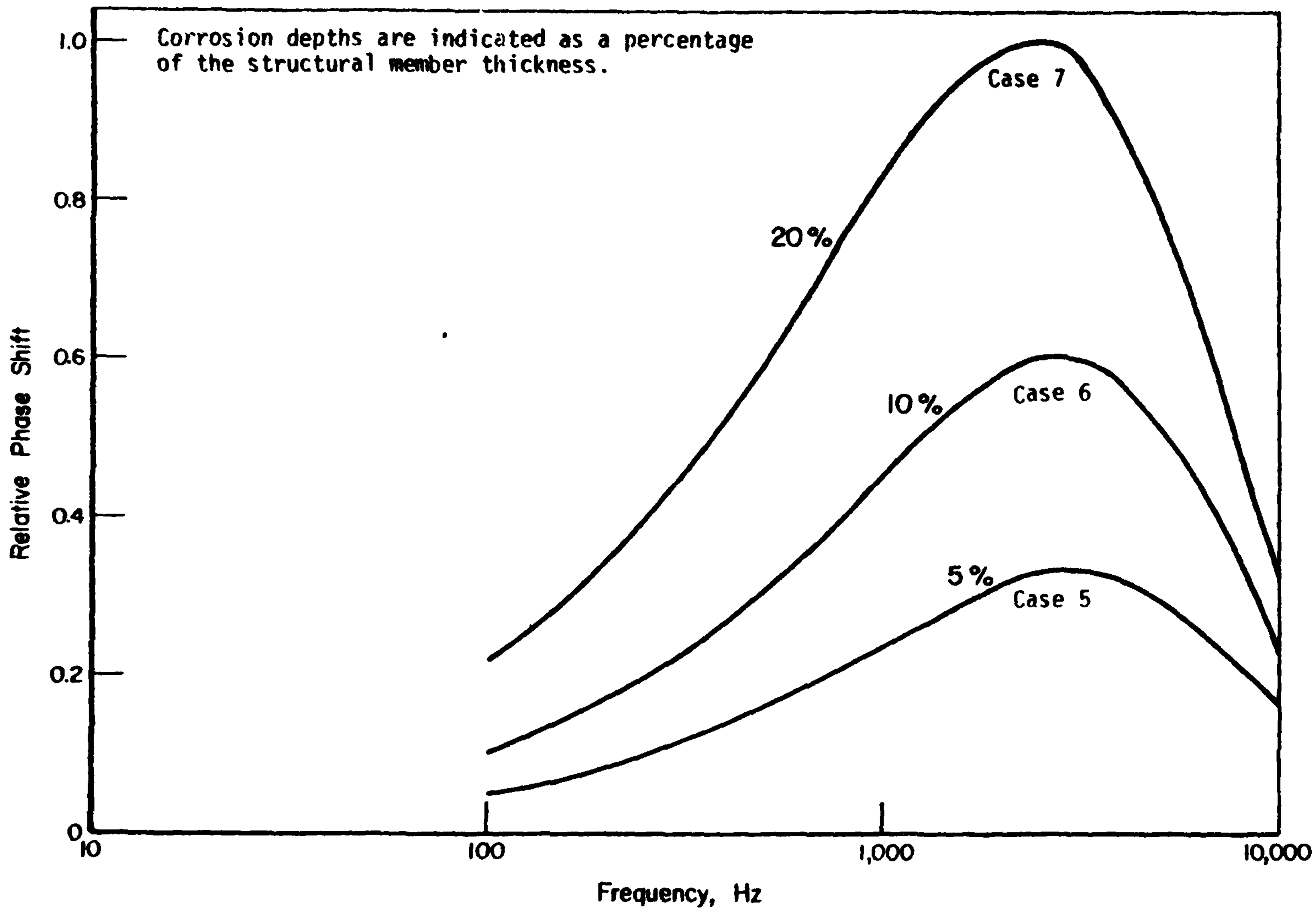



FIGURE 9. OUTER SURFACE DEFECT SENSITIVITY FACTOR VERSUS TEST FREQUENCY FOR DIFFERENT CORROSION DEPTHS (150A COIL)

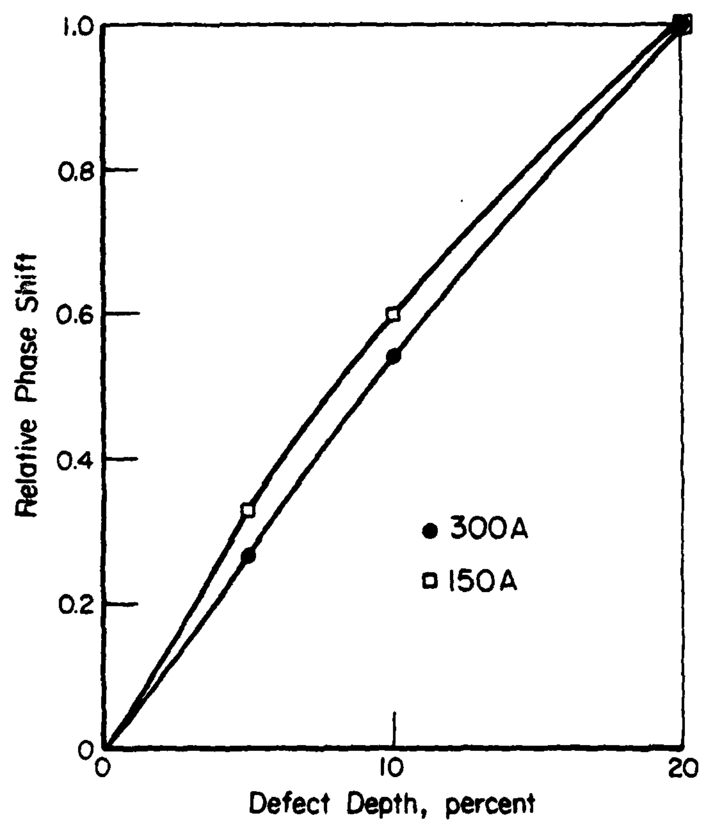



FIGURE 10. EDDY CURRENT PHASE ANGLE VERSUS OUTER SURFACE DEFECT DEPTH (2 kHz)

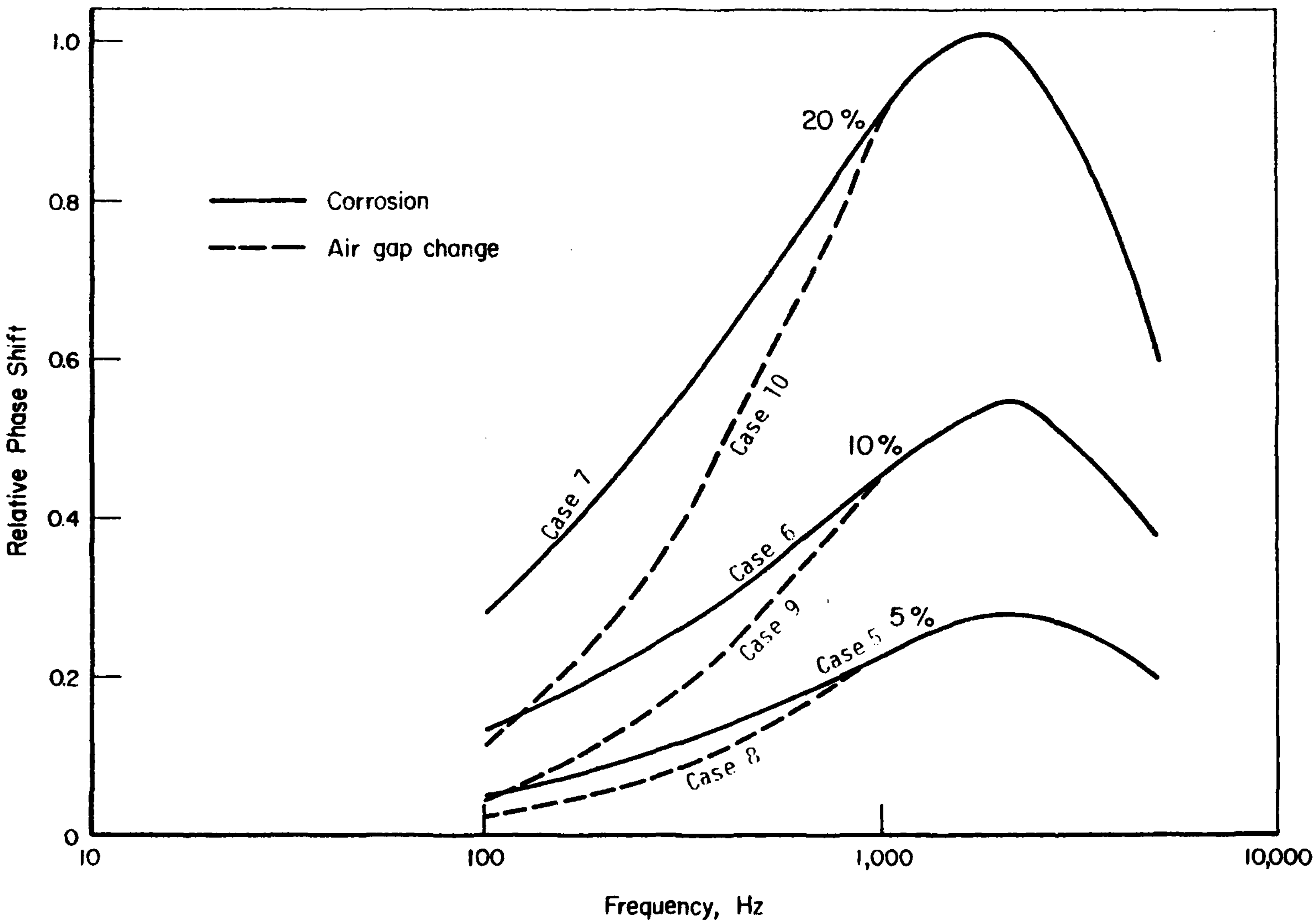



FIGURE 11. SENSITIVITY FACTOR VERSUS FREQUENCY FOR AIR-GAP THICKNESS CHANGES (300A COIL)

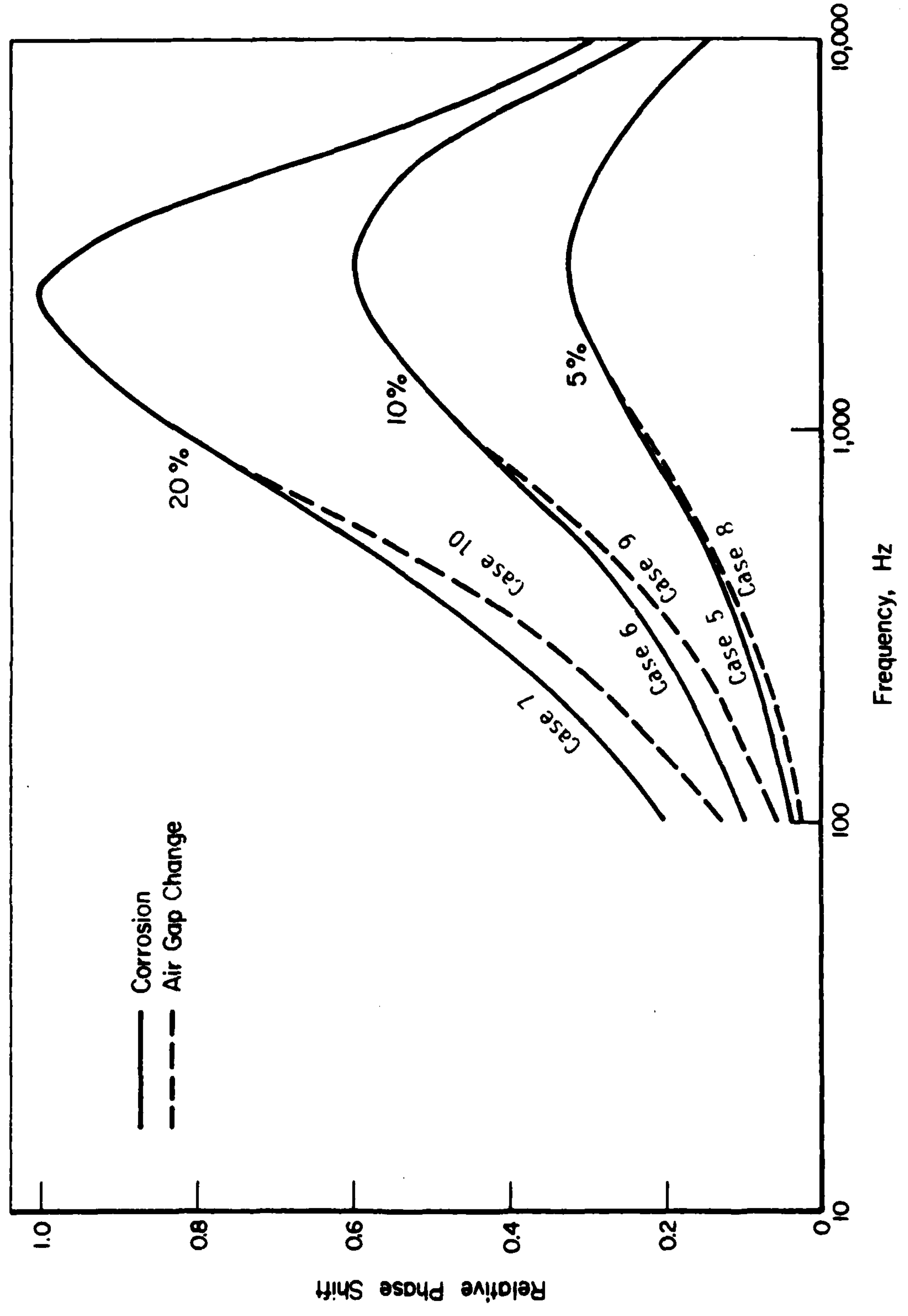



FIGURE 12. SENSITIVITY FACTOR VERSUS FREQUENCY FOR AIR-GAP THICKNESS CHANGES (150A COIL)

## C. TEST IMPLEMENTATION.

1. It is now possible to envision an eddy current system that could perform the necessary inspection and its application. The system itself would necessarily be a dual-frequency system, where the test coil is excited by two frequencies simultaneously. The exact frequencies used would depend upon the thickness of the various metallic members, and if the results presented above are generalized to any structure, the high frequency is determined essentially by the skin thickness, and the low frequency is determined by the combined skin and structural member thickness. For the case examined here, with a 0.05-inch-thick skin and 0.25-inch-thick structural member, the selected frequencies are about 2000 Hz and 200 Hz respectively. Each half of the dual-frequency system would be identical, except for frequency selection, and would consist of a phase-sensitive indicator (probably a meter), a balance control (to set the initial phase reading to zero), and a liftoff compensation null (to reduce the effect of liftoff on the measured phase). Such instruments presently exist as single-frequency instruments; the modifications necessary to make a dual system are rather straightforward.

2. Three calibration curves are required. The first is an extension of Figure 7, and gives the relationship between phase angle (at 200 Hz) and depth of corrosion on the inner surface, as shown in Figure 13. As indicated above, the size of the corroded area is important, and several curves, labeled A1, A2, A3, etc., are shown to emphasize this point. The second set of curves, Figure 14, is an extension of Figure 10, in the same manner as Figure 13 is an extension of Figure 7. Again, various lateral extents of corrosion should be considered in deriving this calibration curve.

3. The last set of curves, Figure 15, is necessary for distinguishing corrosion from sealant thickness changes and is derived from Figure 11 in the following manner. For the three corrosion depths, the phase-angle change at 2 kHz is plotted along the abscissa, and the phase-angle change at 200 Hz is plotted along the ordinate, as shown in Figure 15, to obtain the curve labeled "outer surface corrosion". Similarly, the phase angle change for air-gap or sealant-thickness changes at 200 Hz is plotted versus phase-angle change at 2 kHz to obtain the curve labeled "air-gap change". A third curve is drawn between the two and is labeled "decision curve". Testing then proceeds as described in the following paragraph.

4. Call the low-frequency phase indicator meter A, and the high-frequency indicator meter B. The operator continues testing until meter A registers an indication (either or both meters may be equipped with audible alarms, if desired). He then notices whether meter B also registers an indication. If not, the indication is due to corrosion on the far side of the structural member, and the operator records the indication. If meter B also registers, then the operator must decide whether the indication is due to corrosion of the outer surface, or an air-gap change. This is done by locating the phase angle at 200 Hz versus the phase angle at 2000 Hz of the indication on Figure 15. If the indication lies above the decision curve, it is due to corrosion on the outer surface, and the operator records the indication. If it is below the decision line, it is due to an air-gap thickness change, and the operator continues testing until meter A again responds to an indication. This decision process, which is rather simple in form, is depicted in Figure 16. The applicability to computer-based decision processing is rather obvious.

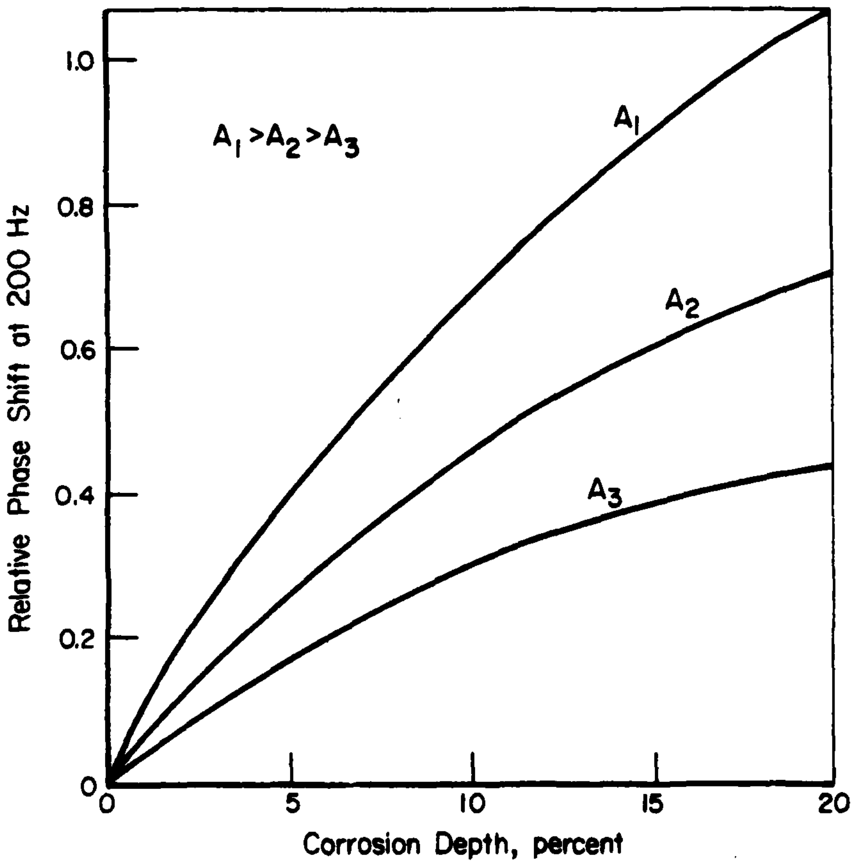



FIGURE 13. PHASE SHIFT VERSUS CORROSION DEPTH FOR VARIOUS SIZES OF INNER SURFACE CORROSION

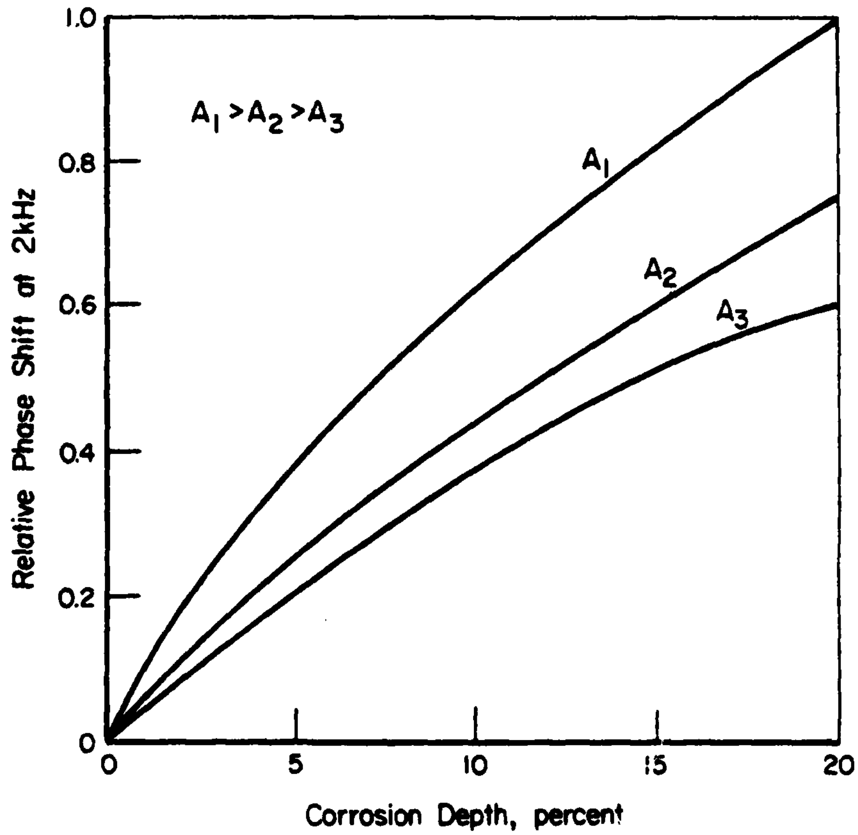



FIGURE 14. PHASE SHIFT VERSUS CORROSION DEPTH FOR VARIOUS SIZES OF OUTER SURFACE CORROSION

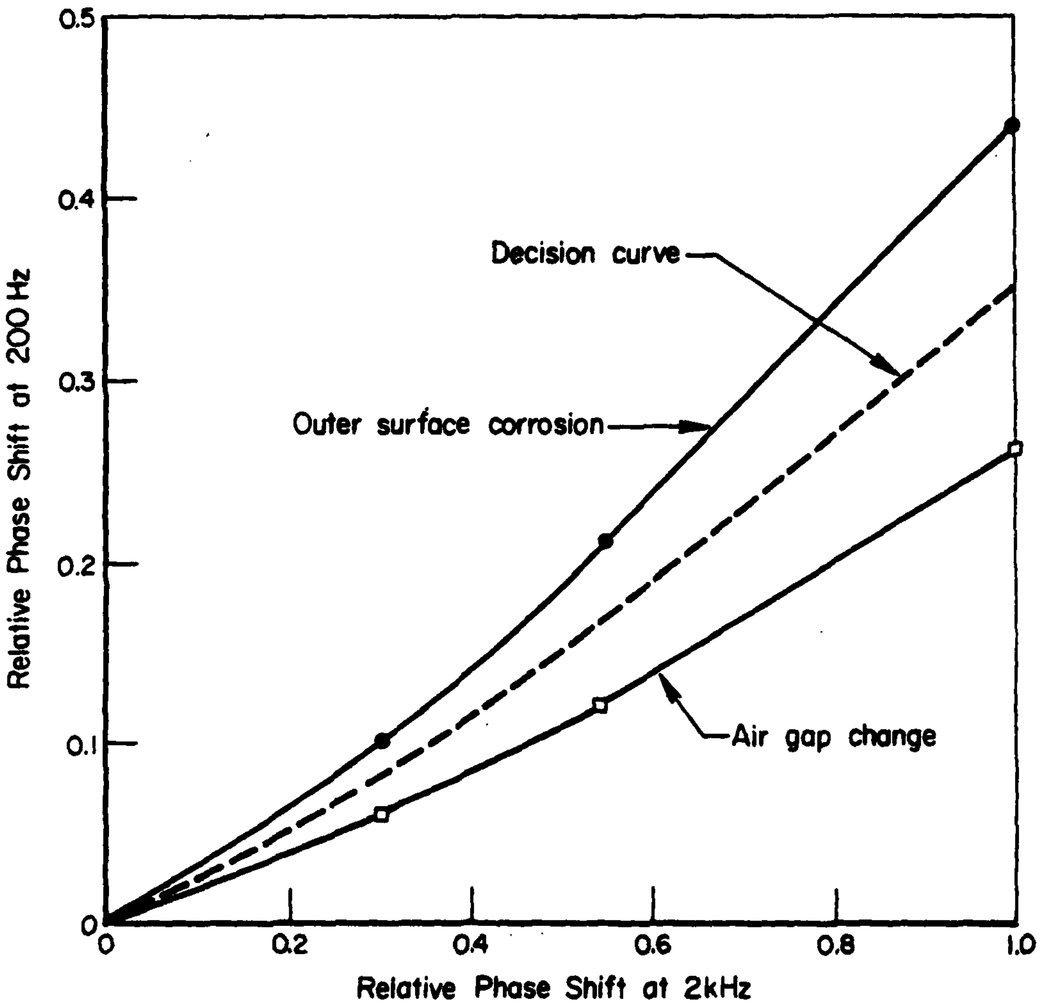



FIGURE 15. DECISION CURVE FOR SEPARATING OUTER SURFACE CORROSION FROM AIR-GAP CHANGES

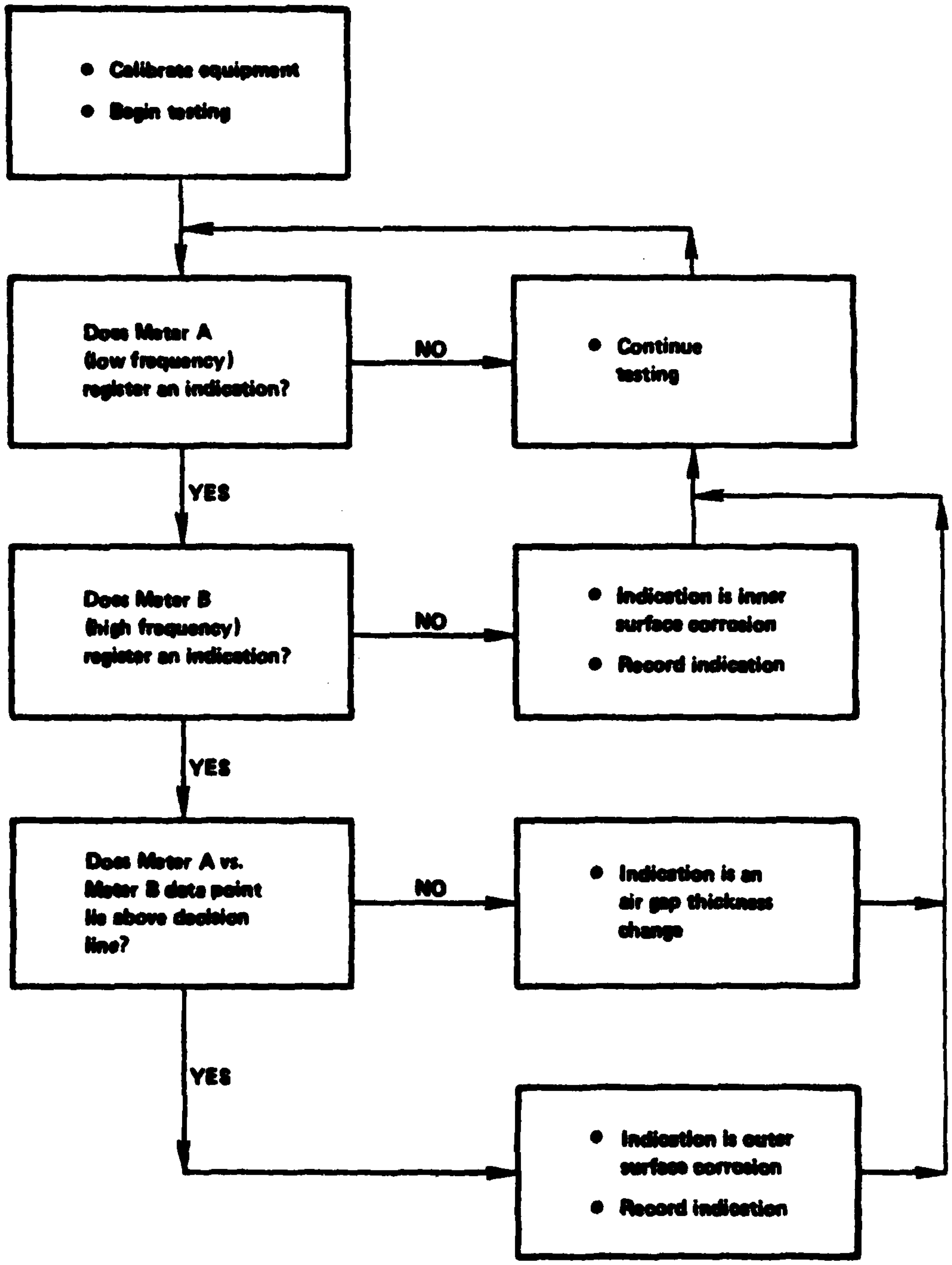



FIGURE 16. EDDY CURRENT CORROSION TESTING DECISION ALGORITHM

# IV. EXPERIMENTAL VERIFICATION OF THE ANALYTICAL MODEL

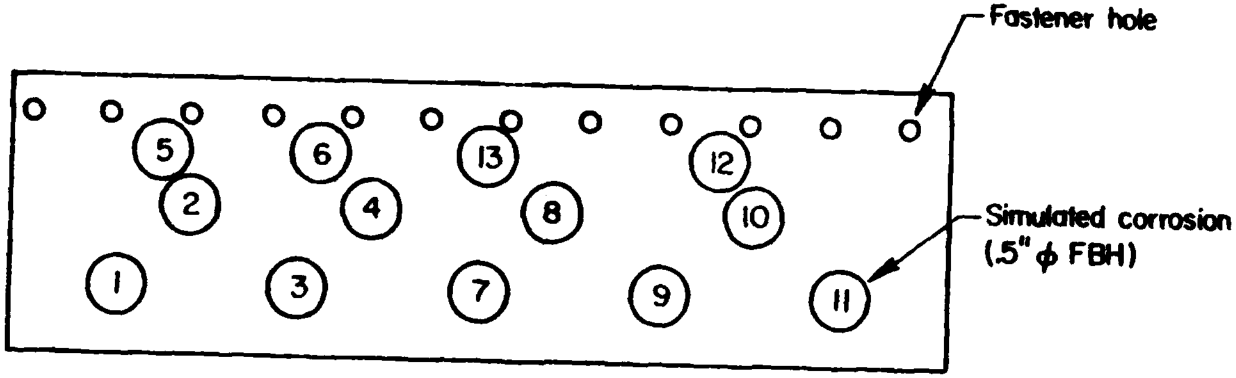
Analytical models are useful because they allow the designer to examine a large variety of test situations with relative ease and speed. The accuracy of any model is suspect, however, because all models, by their very nature, must include assumptions which may or may not be physically justifiable, and because the accuracy of computer calculations is sometimes low. Dodd, the developer of the models used in this study, has verified his results in a few applications, some simple and others more complex. The following is intended as a verification of the models in a somewhat complex test situation.

A. TEST SAMPLES. Two general types of test samples were used in this study. The first type was to test the detection and characterization of simulated OSSC and ISSC, and the second was used to test the results for sealant thickness changes versus outer surface corrosion. The first test sample is depicted in Figure 17, and consisted of a 0.25-inch piece of aluminum (7075-T6) with thirteen 0.5-inch-diameter flat-bottom holes milled into the top and bottom surfaces of the plate to simulate corrosion. As shown, nine holes were in areas away from edges or other discontinuities. A row of fastener holes was also present in the plate and some simulated corrosion areas were placed near these fastener holes to examine the effect of edges on the detection of corrosion. After manufacture, a skin (0.050 inch of 6061-TO) was glued to the sample. The second type of test sample is shown in Figure 18. There were actually five samples of this type made, one of which was a balance sample, fabricated from a 0.25-inch-thick piece and a 0.050-inch-thick piece of 6061-TO. Two of the four samples contained a large area of simulated corrosion; the remaining two had mylar placed between the two aluminum pieces to simulate a sealant or air-gap thickness change comparable to the corrosion depths of the first two samples.

B. INSTRUMENTATION.

1. Two eddy-current instruments were used for the experimental studies. The first was a Tennelec EC 501, which is based upon Dodd's work. The Tennelec is also designed to use the reflection coils, with an operating frequency which varies from 500 Hz to 2 MHz, in 1-2-5 steps. Since the low-frequency end was still too high for some of the required measurements, the EC 501 was supplemented with a Super Halec, sold by Halo Instruments. The frequency range of this instrument is from 10 Hz to 9.9 kHz, depending on the coil size, though the usable range appears to be from 70 Hz up. Transformer coils are also used with this instrument, but are different from the reflection coils designed by Dodd. For the purposes of this report, it was assumed that the predictions generated for the Tennelec-Dodd reflection coils would also hold true, at least in principle, for the Super Halec. That is to say, it was expected that the general trends in the data would be similar, though the numerical values would be different.

2. Both instruments are of the phase-sensitive type; that is, both measure the phase of the voltage induced in the pickup coil, relative to some reference voltage. However, in both instruments, the output is only proportional to phase changes, with the constant of proportionality being different and unknown for both. Thus, all data, both in this section and the




| DEFECT # | DEPTH (% ASM) | CATEGORY (See Figure 5) |
|---|---|---|
| 1 | 5 | C |
| 2 | 10 | C |
| 3 | 20 | C |
| 4 | 40 | C |
| 5 | 5 | C |
| 6 | 10 | C |
| 7 | 100 | C-B |
| 8 | 40 | B |
| 9 | 20 | B |
| 10 | 10 | B |
| 11 | 5 | B |
| 12 | 5 | B |
| 13 | 10 | B |

ASM - Aircraft Structural Member

FBH - Flat Bottom Hole

FIGURE 17. TEST PANEL CONFIGURATION

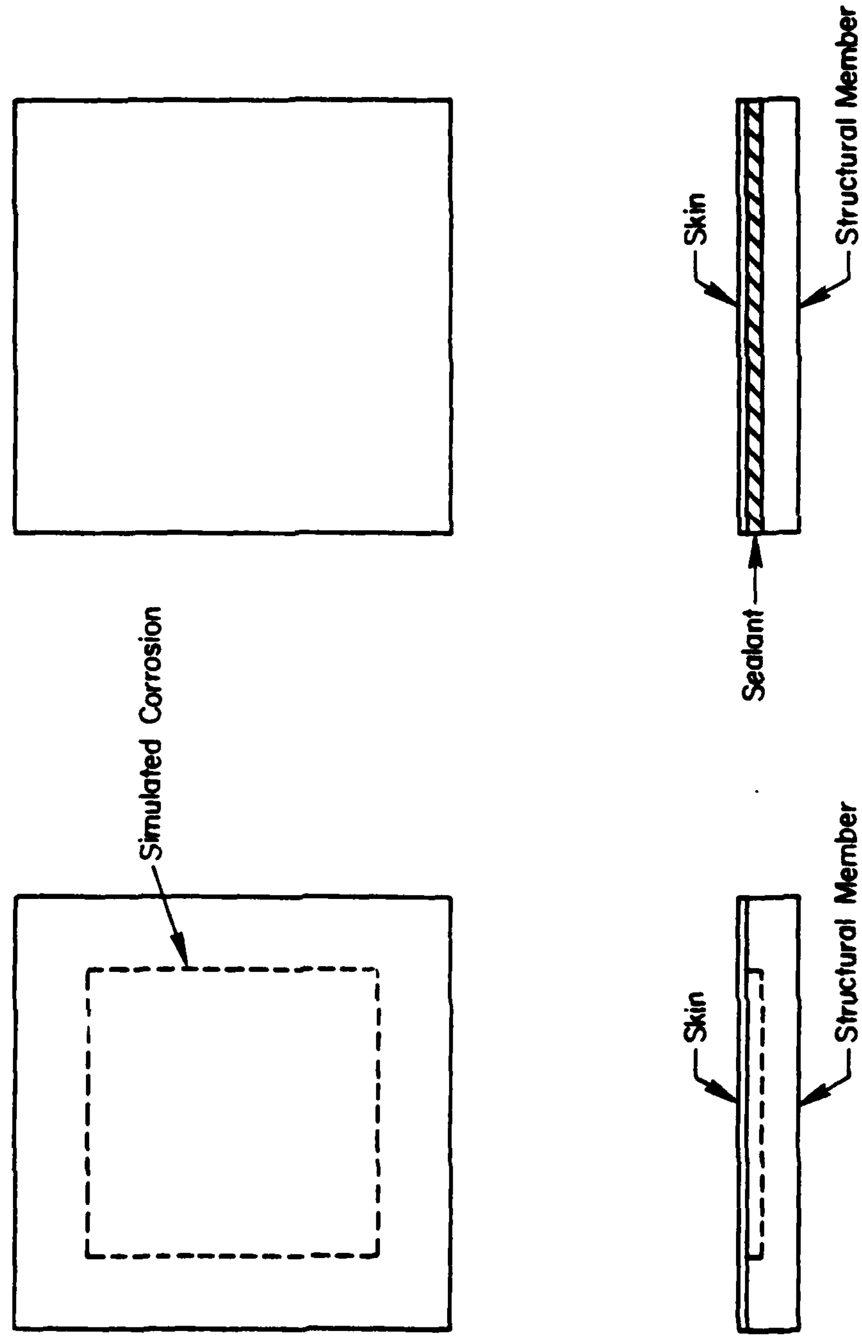



FIGURE 18. TEST PANEL CONFIGURATION - SEALANT THICKNESS CHANGES IN COMBINATION WITH SIMULATED CORROSION

previous section, were normalized to 1 by dividing the output for a given frequency and test situation by the maximum obtained during that series of tests.

## C. RESULTS.

1. A sample panel of the type in Figure 17 was used with both instruments to examine the relationship between phase angle and frequency, for various corrosion depths on the outer surface of the structural member. For both instruments, the test coil was scanned across the plate until a maximum phase change was noted. The plate contained corrosion depths deeper than 20 percent, as noted in Figure 17, but only depths of 5 percent, 10 percent, and 20 percent were modeled; thus, only these depths are shown in Figure 19. Also shown in this figure are the computer-generated plots, for comparison. Note that the predicted results agree very well with the experimental data.

2. The same sample was used with the Super Halec only, since the Tennelec did not have a low enough frequency response to examine the relationship between phase change and inspection frequency for various depth corrosion areas on the inner surface of the structural member. The results, along with the computer-generated curves, appear in Figure 20. In general, the agreement between the two is good, though the agreement at the lower frequencies is not as good. This may be attributed to two major factors: firstly, large volume defects were analyzed, but small volume defects were made in the test sample; and secondly, the coil type used was not exactly like the coil type analyzed.

3. To directly compare the frequency response for near-side corrosion with sealant thickness changes, the areal extent of the two must be the same. It is more difficult to accurately fabricate small area sealant thickness changes, hence the second type of sample, Figure 18, was made with large area corrosion/sealant thickness. The Super Halec was used in this test since the lowest frequency of the Tennelec was again too high for this work.

4. The experimental results are shown in Figure 21; however, the predicted values are not shown, in this case, because the numerical agreement was poor. Note, though, that the trends are well predicted.

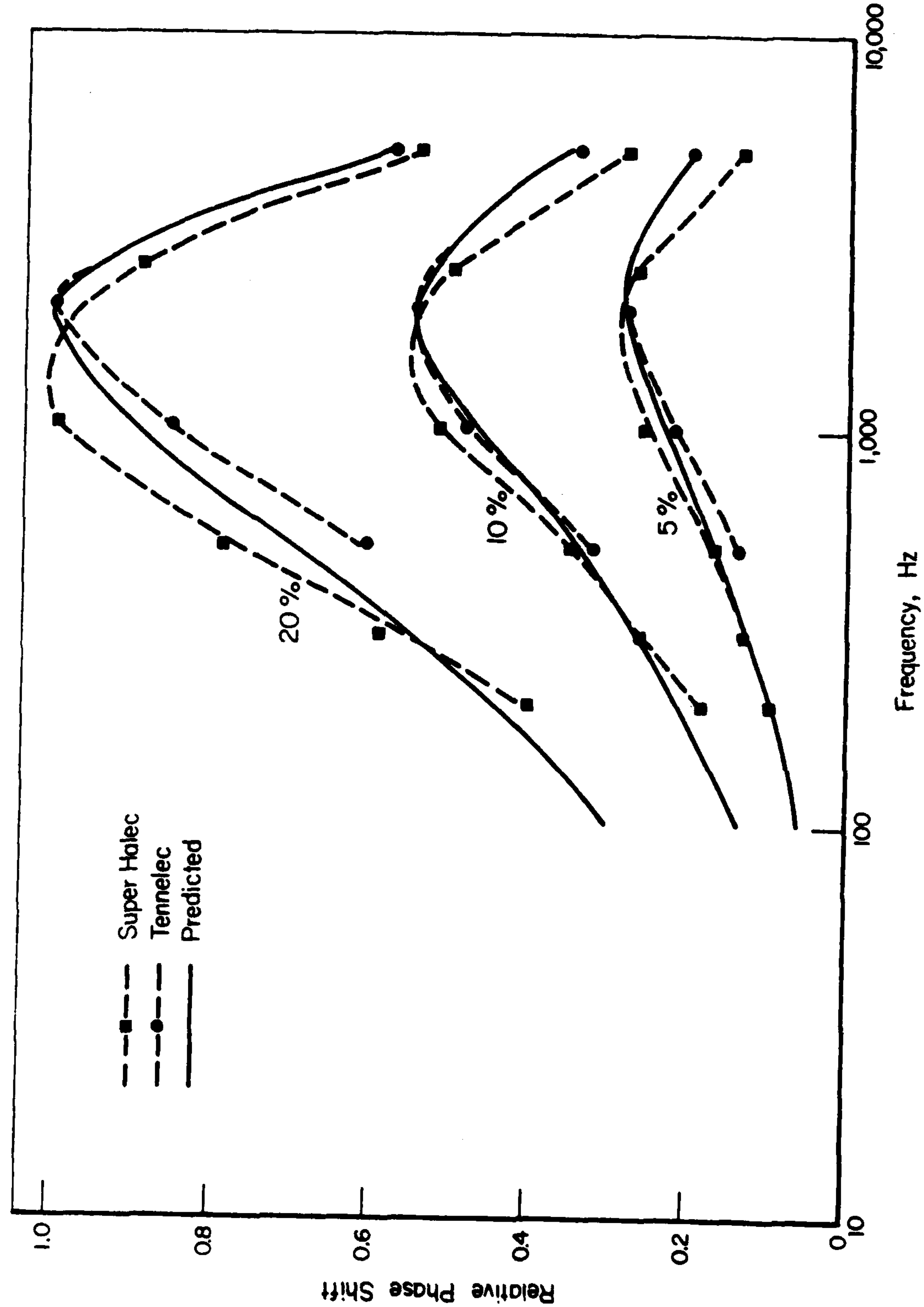



FIGURE 19. EXPERIMENTAL DATA FOR OUTER SURFACE DEFECTS

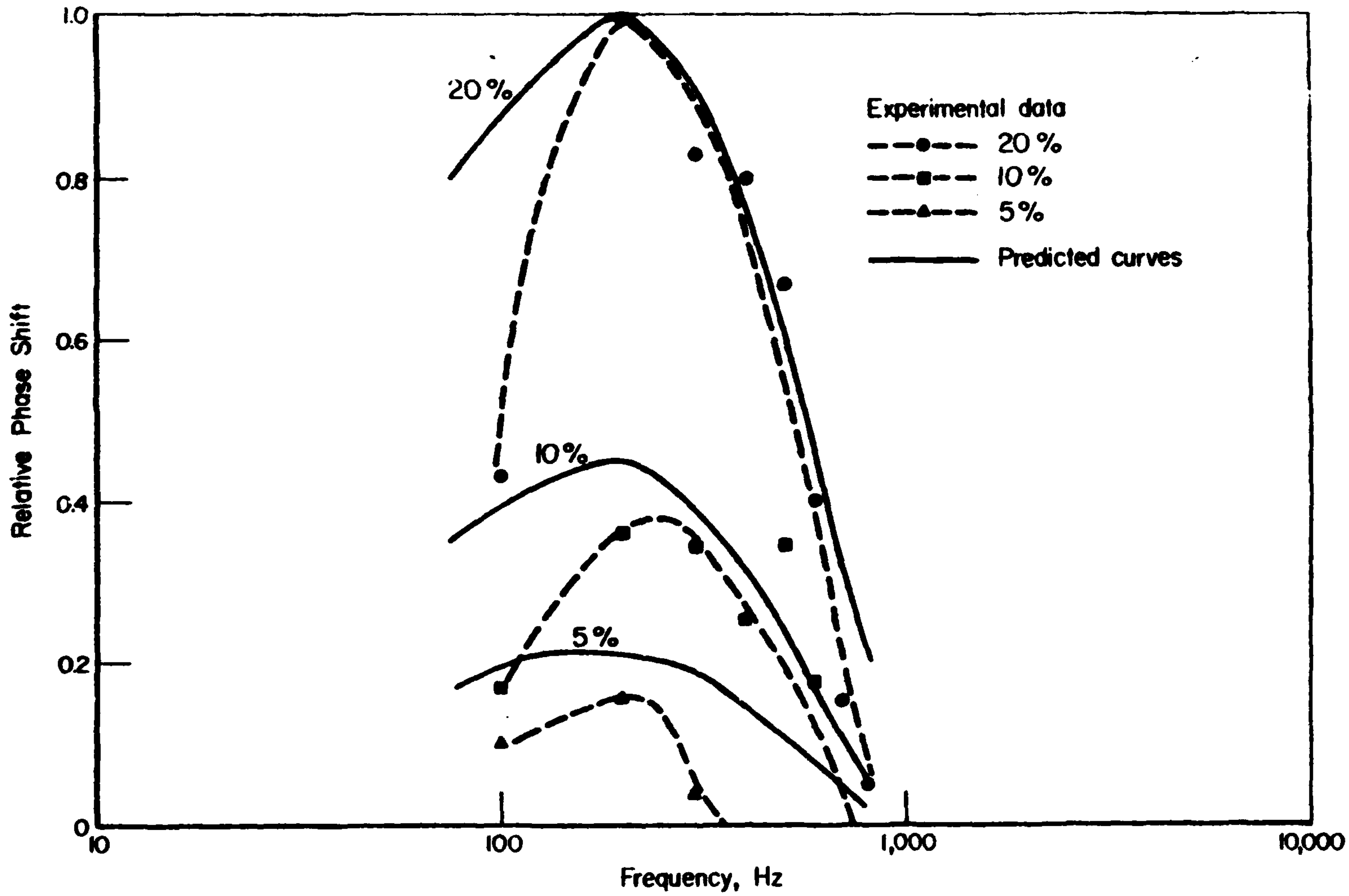



FIGURE 20. EXPERIMENTAL DATA FOR INNER SURFACE CORROSION

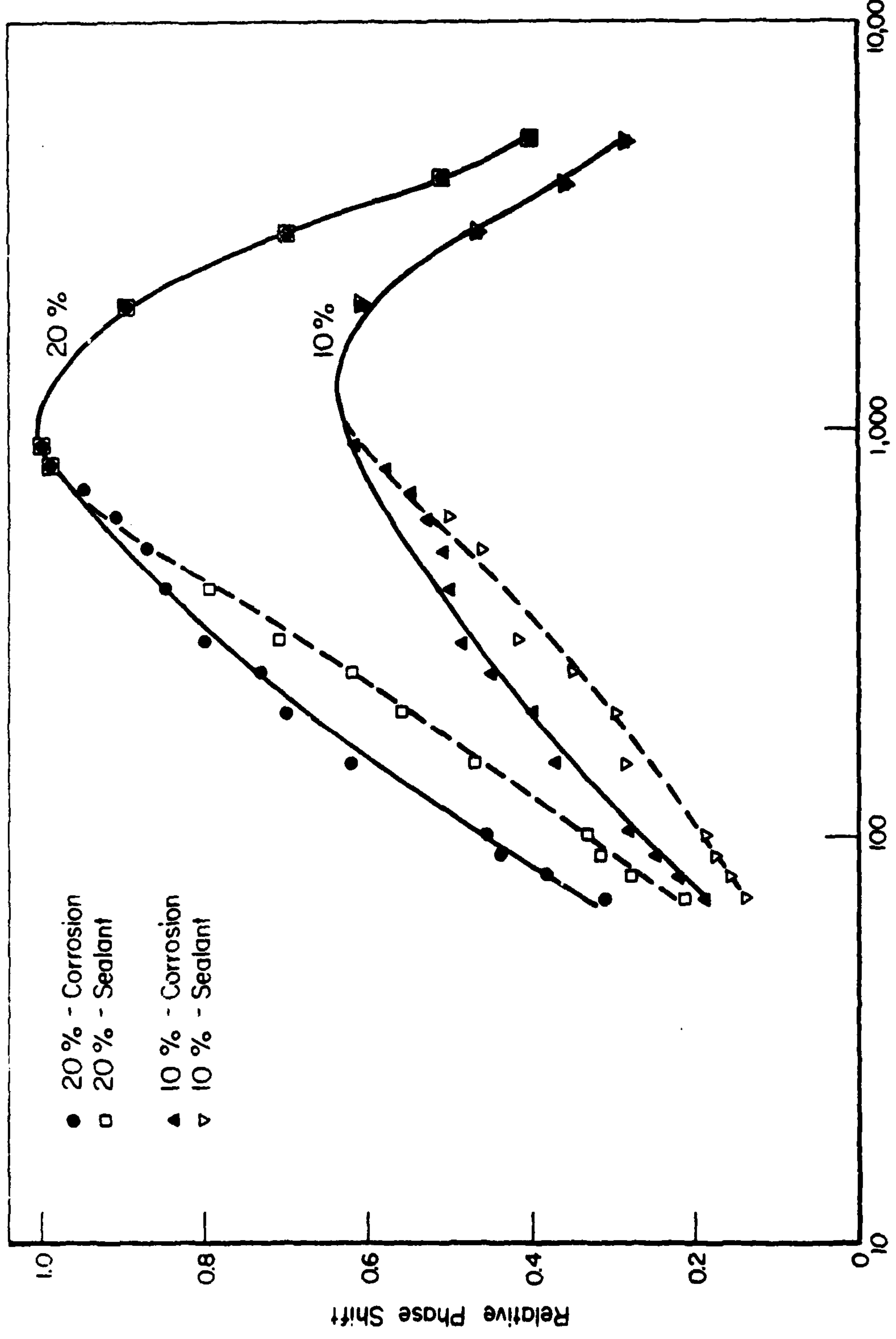



FIGURE 21. EXPERIMENTAL CHARACTERIZATION OF AIR-GAP/SEALANT THICKNESS CHANGES

# APPENDIX A

## COMPUTER PROGRAMS FOR MULTIT, EDTRFC, AND UTILITY SUBROUTINES


| | Page |
|---|---|
| MULTIT . . . . . . . . . . . . . | A-2 |
| EDTRFC . . . . . . . . . . . . . | A-23 |
| UTILITY SUBROUTINES. . . . . . | A-28 |


## INTRODUCTION

The following is a collection of the programs used in the computer modeling of thickness measurements of multilayered structures. The original reference for MULTIT by C. V. Dodd, et al, is contained in the report ORNL-4384 from Oak Ridge National Laboratory entitled "Some Eddy-Current Problems and Their Integral Solutions."

The appendix is divided into three parts: the first contains a slightly modified version of MULTIT, with the associated subroutines, the second is a program EDTRFC (Edit Reflection Coil) which sets up data files for various reflection coils and test object parameters used by MULTIT, and the third is a set of utility subroutines used by both programs for setting up a file structure and for allowing interaction between the computer and the operator. The latter two sections, though written entirely by staff members of the Fabrication and Quality Assurance Section of Battelle Columbus Laboratories for purposes other than this project, are not considered proprietary.

Since these programs were designed for use on our computer system, it is not advisable for some other persons to directly copy them for use in their (different) computer system, and this should be used for informational purposes only. Any person requiring reasonable additional information should contact the staff at BCL for more details.

MULTIT

```
FORTRAN IV      V01C-03B   FRI 19-OCT-79 09:51:05                PAGE 001

        C..
        C..    MULTIT.FOR
        C..    WRITTEN BY C. V. DODD
        C..    ORNL--APRIL, 1973
        C..
        C..    MODIFIED BY D. T. MAYFORD
        C..    BCL--DECEMBER, 1978
        C..
        C..    THIS PROGRAM EVALUATES THE SENSITIVITY TO A THICKNESS
        C..    VARIATION IN ANY GIVEN LAYER OF A MULTI-LAYERED
        C..    MATERIAL
        C..
0001           COMPLEX BETA0,BETA1,BETA,V,V97,TR,GAMMA,MUT,DRIVER
0002           COMPLEX PICKUP
0003           REAL L2,L3,L4,L5,L6,L7,M,N3,N4,MATL
0004           DIMENSION T(10),U(10),RHO(10),M(10),BETA(10)
0005           DIMENSION V(2,2),V97(2,2),TR(2,2),GAMMA(3),DRIVER(3,5)
0006           DIMENSION PICKUP(3,5),RL(5),TMAG(3,5),PHASE(3,5)
0007           DIMENSION SHIFT(3,5),MUT(3,5)
0008           DIMENSION COIL(13), AMP(6), MATL(10,3), ITITL(20), VERB(5)
0009           EQUIVALENCE (R1,COIL(1)),(R0,AMP(1))
             $     ,(T(1),MATL(1,1)),(U(1),MATL(1,2)),(RHO(1),MATL(1,3))
0010           COMMON X,Z,Q1,PI
0011           COMMON /B1/ BETA0,BETA1
0012           COMMON /B2/ R1,R2,R3,R4,L2,L3,L4,L5,L6,N3,N4,
             $     R6,R7,R0,R9,C6,C7,V0,G5,W,F,R5
0013           COMMON /B3/ MUT,DRIVER,PICKUP,AIR1,AIR2
0014           COMMON /B4/ GAGE,XIN,XOUT,XLEN,TURNS,N1A,J1,
             $     PERLAY,XLAY
0015           DATA VERB/'COIL', 'ATT ', 'DRFT', 'STRT', 'EXIT'/
0016           PI = 3.1415926536
0017           RAD = 180./PI
0018         5 JKL = 0
        C..
        C..    ENTER COIL PARAMETERS
        C..
0019           CALL ATTIN(2, 1, 0, ICUR)
0020           READ(2) ITITL,COIL
0021           CALL CLOSE(2)
0022           R5 = (R1+R2)*0.5
0023           DO 10 I=1,9
0024        10 COIL(I) = COIL(I)/R5
0025           TYPE 20, ITITL
0026        20 FORMAT(1X,20A2/)
0027           CALL ATTIN(2,2,0,ICUR)
0028           READ(2) ITITL, N9, MATL
0029           CALL CLOSE(2)
0030           TYPE 20, ITITL
0031           TYPE 21
0032        21 FORMAT('$ENTER LAYER NO. WITH THICKNESS VAR.: ')
0033           ACCEPT 22,N8
0034        22 FORMAT(I2)
0035           N8 = N8+1
0036           CALL ATTIN(2,3,0,ICUR)
```

```
      READ(2) ITITL, AMP
      CALL CLOSE(2)
      TYPE 20,ITITL
      TYPE 23
   23 FORMAT('$ENTER OPERATING FREQ.: ')
      ACCEPT 24, F
   24 FORMAT(F10.0)
      T9 = .05
      IF(N9.LT.3.OR.N8.GE.N9.OR.N8.EQ.1)GO TO 1110
      L7 = L3-2.0*(L4+L5)
  105 W = 2.0*PI*F
      IF(JKL.NE.0) GO TO 115
      TYPE 110
  110 FORMAT('  N',13X,'THICK.(IN)',4X,'R(M-OHM CM)',3X,
     $     'M,SIGMA',10X,'U')
  115 DO 150 I= 1,N9
      IF(RHO(I).GT.1.0E9) GO TO 120
      M(I) = 0.5094*U(I)*F*R5*R5/RHO(I)
      GO TO 125
  120 M(I) = 0.0
  125 IF(JKL.NE.0) GO TO 150
  130 TYPE 140,I ,T(I),RHO(I),M(I),U(I)
  140 FORMAT(' ',I2,12X,1PE12.5,2X,E12.5,2X,E12.5,2X,0PF6.2)
  150 CONTINUE
      T(N9)= 0.0
      T0 = T(N8)
      T9 = 0.05
      IF(JKL.NE.0)GO TO 205
      TVAR = 100.0*T9
C..
C..   PRINT OUT SYSTEM PARAMETERS
      TYPE 155,N8,TVAR
  155 FORMAT(' THICKNESS VARIATION OF',I3,'TH LAYER IS +-'
     $     ,F6.2,'%')
      TYPE 570
      TYPE 160,R1,R2,L3
  160 FORMAT(' R1=',F8.5,3X,'R2=',F8.5,3X,'DRIVER LENGTH=',F8.5)
      TYPE 170,R3,R4,L4
  170 FORMAT(' R3=',F8.5,3X,'R4=',F8.5,3X,'PICKUP LENGTH=',F8.5)
      TYPE 180,R5,F
  180 FORMAT(' COIL MEAN RADIUS=',F8.5,' INCHES',3X,
     $     'OPERATING FREQUENCY=',1PE12.5)
      TYPE 190,L5
  190 FORMAT(' PICKUP RECESSED',F8.5)
      TYPE 200,L6,L2
  200 FORMAT(' MIN LIFT-OFF=',F8.5,3X,'LIFT-OFF INCREMENT=',F8.5)
C..
C..   INTEGRATION BEGINS HERE. THE MUTUAL, DRIVER, AND
C..   PICKUP INDUCTANCES, ALONG WITH THEIR AIR VALUES ARE CALCULATED
C..
  205 S1 = 0.01
      S2 = 5.0
      B1 = 0.0
      B2 = S2
```

```
      DO 207 I=1,3
      DO 207 J=1,5
      MUT(I,J) = (0.0, 0.0)
      DRIVER(I,J) = (0.0, 0.0)
  207 PICKUP(I,J) = (0.0, 0.0)
      AIR1 = 0.0
      AIR2 = 0.0
  210 I1 = (B2-B1)/S1
      X = B1-S1/2.0
      DO 490 IDX=1,I1
      X = X+S1
      TEST = X*L3
      IF(TEST.GT.20.0) GO TO 220
      W3 = EXP(-TEST)
      GO TO 230
  220 W3 = 0.0
  230 W8 = 1.0-W3
      TEST = X*L4
      IF(TEST.GT.20.0) GO TO 240
      W4 = EXP(-TEST)
      GO TO 250
  240 W4 = 0.0
  250 W9 = 1.0-W4
      TEST = X*L7
      IF(TEST.GT.20.0) GO TO 260
      W7 = EXP(-TEST)
      GO TO 270
  260 W7 = 0.0
  270 W5 = EXP(-X*L5)
      W0 = 1.0-W7*W4
      TEST = X*L6
      IF(TEST.GT.20.0) GO TO 485
      W6 = EXP(-2.0*TEST)
      Z = X*R2
      Q1 = R2
C..   SUBROUTINE BESSEL EVALUATES THE INTEGRAL OF X*J1(X)
      CALL BESSEL(VAL2)
      Z = X*R1
      Q1 = R1
      CALL BESSEL(VAL1)
      Z = X*R4
      Q1 = R4
      CALL BESSEL(VAL4)
      Z = X*R3
      Q1 = R3
      CALL BESSEL(VAL3)
      S3 = S1*(VAL2-VAL1)*(VAL4-VAL3)
      S4 = S1*(VAL2-VAL1)*(VAL2-VAL1)
      S5 = S1*(VAL4-VAL3)*(VAL4-VAL3)
      A5 = W6*W5*W8*W9*W0*S3
      A6 = W6*W8*W8*S4
      A7 = W6*W5*W5*W9*W9*W0*W0*S5
      IF(X.GT.30.0) GO TO 485
C..   THE LOWEST SIGNIFICANT LAYER,N7, IS DETERMINED
```

```
              QSUM = 0.0
              N = N9
              TEST = X*X*1.0E-5
        280   IF(M(N).LT.TEST) GO TO 290
              BETA(N) = CSQRT(CMPLX(X*X,M(N)))/U(N)
              GO TO 300
        290   BETA(N) = CMPLX(X,0.0)
        300   QSUM = QSUM+REAL(BETA(N))*T(N)/R5
              IF(QSUM.GT.20.0.OR.N.EQ.1) GO TO 310
              N = N-1
              GO TO 280
        310   N7 = N
      C..     THE MATRIX ELEMENTS V(N7+1,N7)L,2 (L=1,2) ARE
      C..     CALCULATED
              V(1,2) = BETA(N+1)-BETA(N)
              V(2,2) = BETA(N+1)+BETA(N)
      C..     THE TOTAL MATRIX V(N9,N7) IS CALCULATED BETWEEN HERE
      C..     AND LINE 430.  THE GAMMA FACTOR IS JUST THE RATIO
      C..     V(N9,N7)1,2/V(N9,N7)(2,2.  SUBROUTINE XFORM CALCULATES
      C..     THE TRANSFORMATION MATRIX T(M+1,M)I,J AND SUBROUTINE
      C..     MATRIX THEN CALCULATES V(K,L)I,J
              IF(N8.EQ.(N7+1)) GO TO 360
              BETAO = BETA(N7+1)
              N6 = N8
              IF(N8.GT.(N7+1)) GO TO 340
              N6= N9
        340   IDX1 = N7+2
              IF(IDX1.GT.N6) GO TO 355
              DO 350 N=IDX1,N6
              BETA1 = BETA(N)
              CALL XFORM(N,TR,R5,U,T)
              JUMP = 1
              CALL MATRIX(JUMP,V,TR)
        350   BETAO = BETA1
        355   IF(N8.LT.(N7+1)) GO TO 410
        360   V97(1,2) = V(1,2)
              V97(2,2) = V(2,2)
              IF(N8.EQ.(N9-1)) GO TO 400
              N = N8+2
              BETAO = BETA(N8+1)
              BETA1 = BETA(N)
              CALL XFORM(N,TR,R5,U,T)
              DO 370 I=1,2
              DO 370 J=1,2
        370   V(I,J) = TR(I,J)
              IF(N8.EQ.(N9-2)) GO TO 390
              BETAO = BETA(N8+2)
              IDX1 = N8+3
              IF(IDX1.GT.N9) GO TO 390
              DO 380 N=IDX1,N9
              BETA1 = BETA(N)
              CALL XFORM(N,TR,R5,U,T)
              JUMP = 0
              CALL MATRIX(JUMP,V,TR)
```

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```
380 BETA0 = BETA1
390 V97(1,1) = V(1,2)
    V97(2,1) = V(2,2)
400 N = N8+1
    BETA0 = BETA(N8)
    BETA1 = BETA(N)
410 DO 430 I=1,3
    IF(N8.LT.(N7+1))GO TO 430
    AI = I
    T(N-1) = T0*(1.0+(AI-2.0)*T9)
    CALL XFORM(N,TR,R5,U,T)
    V(1,2) = V97(1,2)
    V(2,2) = V97(2,2)
    JUMP = 1
    CALL MATRIX(JUMP,V,TR)
    IF(N8.EQ.(N9-1)) GO TO 430
    DO 420 J=1,2
    TR(J,1) = V(J,1)
420 TR(J,2) = V97(J,1)
    JUMP = 1
    CALL MATRIX(JUMP,V,TR)
430 GAMMA(I) = V(1,2)/V(2,2)
    T(N8) = T0
    RL(1) = 1.0
    TEST = X*L2
    IF (TEST.GT.20.0) GO TO 440
    W2 = EXP(-2.0*TEST)
    GO TO 450
440 W2 = 0.0
450 DO 470 K=2,5
    AK = K
    TEST = AK*X*L2
    IF(TEST.GT.20.0) GO TO 460
    RL(K) = W2*RL(K-1)
    GO TO 470
460 RL(K) = 0.0
470 CONTINUE
    DO 480 J=1,3
    DO 480 K=1,5
    MUT(J,K) = MUT(J,K)+GAMMA(J)*RL(K)*A5
    DRIVER(J,K) = DRIVER(J,K)+GAMMA(J)*RL(K)*A6
480 PICKUP(J,K) = PICKUP(J,K)+GAMMA(J)*RL(K)*A7
485 AIR1 = AIR1+2.0*S4*(X*L3-W8)
    AIR2 = AIR2+S5*(4.0*(X*L4-W9)-2.0*W7*W9*W9)
490 CONTINUE
    B1 = B2
    B2 = B2+S2
    S1 = 0.05
    IF(X.LT.9.0) GO TO 210
    S1 = 0.1
    IF(X.LT.29.0) GO TO 210
    S1 = 0.2
    IF (X.LT.39.0) GO TO 210
    S1 = 0.5
```

```
          IF(X.LT.79.0) GO TO 210
      C..   THE INTEGRATION ENDS HERE
          IF(JKL.NE.0) GO TO 880
      C..
      C..   NEXT, THE INDUCTANCES, VOLTAGES, AND PHASE SHIFTS
      C..   ARE CALCULATED AND PRINTED
      500 CALL CIRCT(TMAG,PHASE,Q0,T1,T2)
          CALL PHASET(TMAG,PHASE,SHIFT,V1,SET)
          TYPE 510
      510 FORMAT(' DRIVER RES',4X,'INDUCTANCE',4X,
         $     'NO TURNS',6X,'SHUNT CAP',5X,'NOR IM PT')
          Q1 = Q0*T1*T1*AIR1/W
          Q2 = (REAL(DRIVER(2,3))+AIR1)/AIR1
          Q3 = Q0*T2*T2*AIR2/W
          Q4 = (REAL(PICKUP(2,3))+AIR2)/AIR2
          TYPE 520,R6,Q1,N3,C6,Q2
      520 FORMAT(' ',1PE12.5,2X,E12.5,2X,0PF8.1,6X,1PE12.5,
         $     2X,0PF9.6)
          TYPE 530
      530 FORMAT(' PICKUP RES',4X,'INDUCTANCE',4X,'NO TURNS',6X,
         $     'SHUNT CAP',5X,'NOR IM PT')
          TYPE 520,R7,Q3,N4,C7,Q4
          TYPE 540
      540 FORMAT(' DRIVING VOLT',2X,'SERIES RES',4X,
         $     'AMP GAIN',6X,'INPUT IMP')
          TYPE 550,V0,R0,G5,R9
      550 FORMAT(' ',F5.1,9X,1PE12.5,2X,0PF8.1,6X,1PE12.5)
          TYPE 560,V1
      560 FORMAT(' DISCRIMINATOR VOLTAGE=',1PE12.5)
          TYPE 570
          RL(1)=L6
      570 FORMAT(' ')
          DO 580 I=2,5
      580 RL(I) = L2+RL(I-1)
          TYPE 590,RL
      590 FORMAT(' ',4(F6.3,8X),F6.3)
          TYPE 570
          DO 600 I=1,3
          TYPE 610,(TMAG(I,J),J=1,5)
          TYPE 610,(PHASE(I,J),J=1,5)
          TYPE 610, (SHIFT(I,J),J=1,5)
          TYPE 570
      600 CONTINUE
      610 FORMAT(1X,4(1PE12.5,2X),E12.5)
          CALL SENS(SHIFT,RAD,SEN)
      C..
      C..   THE USER NEXT SELECTS ONE OF FIVE POSSIBILITIES
      C..
      620 CALL COMAND(VERB,5,N5,'COMMAND: ')
          GO TO (650,780,860,5,1110),N5
      C..
      C..   THE FIRST POSSIBILITY ALLOWS THE USER TO ALTER THE
      C..   COIL DESIGN BY INPUTTING THE REQUESTED INTEGER DATA
      650 TYPE 660
```

```
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0303      660 FORMAT(' DRIVER WIRE GAGE, TURNS, PICKUP WIRE GAGE,TURNS')
0304          TYPE 570
0305          ACCEPT 670,N1A,N2A,N3A,N4A
0306      670 FORMAT(4I4)
0307          IF(N1A*N2A.EQ.0) GO TO 680
0309          GAGE = N1A
0310          XIN = R1*R5
0311          XOUT = R2*R5
0312          XLEN = L3*R5
0313          TURNS = N2A
0314          N3 = N2A
0315          N1A = -1
0316          J1 = 1
0317          CALL GAGER(R6)
0318          GO TO 700
0319      680 IF(N1A.EQ.0) GO TO 690
0321          GAGE = N1A
0322          XIN = R1*R5
0323          XOUT = R2*R5
0324          XLEN = L3*R5
0325          J1 = 1
0326          CALL GAGER(R6)
0327          N3 = TURNS
0328          GO TO 700
0329      690 IF(N2A.EQ.0) GO TO 720
0331          N3 = N2A
0332          TURNS = N2A
0333          XIN = R1*R5
0334          XOUT = R2*R5
0335          XLEN = L3*R5
0336          J1 = 0
0337          CALL GAGER(R6)
0338      700 TYPE 710,TURNS,GAGE,PERLAY,XLAY,R6
0339      710 FORMAT(' DRIVER',F6.1,' TURNS OF #',F5.1,'WIRE',
         $     F5.1,'/LAYER',F5.1,'LAYERS',1PE12.5,'OHMS')
0340      720 IF(N3A*N4A.EQ.0) GO TO 730
0342          GAGE = N3A
0343          TURNS = N4A
0344          N4 = N4A
0345          XIN = R3*R5
0346          XOUT = R4*R5
0347          XLEN = L4*R5
0348          J1 = 1
0349          CALL GAGER(R7)
0350          R7 = 2.0*R7
0351          GO TO 750
0352      730 IF(N3A.EQ.0) GO TO 740
0354          GAGE = N3A
0355          XIN = R3*R5
0356          XOUT = R4*R5
0357          XLEN = L4*R5
0358          J1 = 1
0359          CALL GAGER(R7)
0360          R7 = 2.0*R7
```

```
            N4 = TURNS
            GO TO 750
      740 IF(N4A.EQ.0) GO TO 770
            N4 = N4A
            TURNS = N4A
            XIN = R3*R5
            XOUT = R4*R5
            XLEN = L4*R5
            J1 = 0
            CALL GAGER(R7)
            R7 = 2.0*R7
      750 TYPE 760,TURNS,GAGE,PERLAY,XLAY,R7
      760 FORMAT(' PICKUP',F6.1,' TURNS EA#',F5.1,'WIRE',
         $     F5.1,'/LAYER',F5.1,'LAYERS',1PE12.5,'OHMS')
      770 GO TO 500
C..
C..   THE SECOND POSSIBILITY ALLOWS THE USER TO ALTER THE
C..   ATTENUATOR DESIGN BY INPUTTING THE DATA REQUESTED IN
C..   E FIELD FORMAT
      780 TYPE 790
      790 FORMAT(' DRIVER SERIES RES, SHUNT CAP, PICKUP SHUNT RES,
         $      SHUNT CAP')
            TYPE 570
            ACCEPT 800,P1,P2,P3,P4
      800 FORMAT(4F10.0)
            IF(P1.EQ.0.0) GO TO 810
            R0 = P1
      810 IF(P2.EQ.0.0) GO TO 820
            C6 = P2
      820 IF(P3.EQ.0.0) GO TO 830
            R9 = P3
      830 IF(P4.EQ.0.0) GO TO 840
            C7 = P4
      840 Q5 = 1.0/(W*SQRT(Q1*Q2*C6))
            Q6 = SQRT(Q1*Q2/C6)
            Q7 = R0/(W*Q1*Q2)
            Q8 = 1.0/(W*SQRT(Q3*Q4*C7))
            Q9 = SQRT(Q3*Q4/C7)
            Q10 = R9/(W*Q3*Q4)
            TYPE 850,Q5,Q6,Q7
      850 FORMAT(' DVR CKT',1PE12.5,' BELOW RES',1PE12.5,
         $     ' OPT RES',1PE12.5,' RES/REACT.')
            TYPE 855,Q8,Q9,Q10
      855 FORMAT(' P-U CKT',1PE12.5,' BELOW RES',1PE12.5,
         $     ' OPT RES',1PE12.5,' RES/REACT.')
            GO TO 500
C..
C..   THE THIRD POSSIBILITY ALLOWS THE USER TO EXAMINE THE
C..   EFFECT OF DRIFTS ON THE CIRCUIT
      860 TYPE 870
      870 FORMAT(' SYSTEM DRIFT VARIATIONS')
            DR1 = 0.01
            DR2 = 0.01
            DR3 = 0.01
```

```
0409          DR4 = 0.01
0410          DR5 = 0.01
0411          DR6 = 0.01
0412          DR7 = 0.01
0413          DR8 = 0.01
0414          DR9 = 0.01
0415          GO TO 890
0416      880 CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0417          GO TO (1070,1100),JKL
0418      890 TYPE 900
0419      900 FORMAT(' %VARIATION',3X,'PARAMETER VAR',1X,
         $     'RADIANS',7X,'DEGREES',7X,'% OF RANGE')
0420          IF(DR1.EQ.0.0) GO TO 930
0422          R6 = R6*(1.0+DR1)
0423          DR100 = 100.0*DR1
0424          TYPE 920,DR100
0425      920 FORMAT('$',F4.1,10X,'DRIVER RES   ')
0426          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0427          R6 = R6/(1.0+DR1)
0428      930 IF(DR2.EQ.0.) GO TO 950
0430          R7 = R7*(1.0+DR2)
0431          DR100 = 100.*DR2
0432          TYPE 940,DR100
0433      940 FORMAT('$',F4.1,10X,'PICKUP RES   ')
0434          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0435          R7 = R7/(1.0+DR2)
0436      950 IF(DR3.EQ.0.0) GO TO 970
0438          C6 = C6*(1.0+DR3)
0439          DR100 = 100.0*DR3
0440          TYPE 960,DR100
0441      960 FORMAT('$',F4.1,10X,'DVR SHUNT CAP')
0442          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0443          C6 = C6/(1.0+DR3)
0444      970 IF(DR4.EQ.0.0) GO TO 990
0446          C7 = C7*(1.0+DR4)
0447          DR100 = 100.*DR4
0448          TYPE 980,DR100
0449      980 FORMAT('$',F4.1,10X,'P-U SHUNT CAP')
0450          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0451          C7 = C7/(1.0+DR4)
0452      990 IF(DR5.EQ.0.0) GO TO 1010
0454          R0 = R0*(1.0+DR5)
0455          DR100 = 100.*DR5
0456          TYPE 1000,DR100
0457     1000 FORMAT('$',F4.1,10X,'SERIES RES   ')
0458          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0459          R0 = R0/(1.0+DR5)
0460     1010 IF(DR6.EQ.0.0) GO TO 1030
0462          R9 = R9*(1.0+DR6)
0463          DR100 = 100.*DR6
0464          TYPE 1020,DR100
0465     1020 FORMAT('$',F4.1,10X,'AMP INPUT RES')
0466          CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
0467          R9 = R9/(1.0+DR6)
```

```
1030 IF(DR7.EQ.0.0) GO TO 1050
     VO = VO*(1.0+DR7)
     DR100 = 100.*DR7
     TYPE 1040,DR100
1040 FORMAT('$',F4.1,10X,'APPLIED VOLT ')
     CALL CIRCT1(SET,V1,SHIFT,RAD,SEN)
     VO = VO/(1.0+DR7)
1050 IF(DR8.EQ.0.0) GO TO 1080
     F = F*(1.0+DR8)
     DR100 = 100.*DR8
     TYPE 1060,DR100
1060 FORMAT('$',F4.1,10X,'FREQUENCY    ')
     JKL = 1
     GO TO 105
1070 F = F/(1.0+DR8)
     JKL = 0
1080 IF(DR9.EQ.0) GO TO 620
     R5 = R5*(1.0+DR9)
     DR100 = 100.*DR9
     TYPE 1090,DR100
1090 FORMAT('$',F4.1,10X,'MEAN RADIUS  ')
     JKL = 2
     GO TO 105
1100 R5 = R5/(1.0+DR9)
     JKL = 0
     GO TO 620
C..
C..    THE FOURTH POSSIBILITY RETURNS TO PROGRAM START
C..
C..    THE FIFTH POSSIBILTY ENDS ALL CALCULATIONS
C..
1110 CALL EXIT
     END
```

```
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      SUBROUTINE BESSEL(VAL)
      COMMON X, Z, Q1, PI
      IF(Z.GT.5.0) GO TO 1510
      L = 2.0*Z+3.0
      F1 = 0.5*Q1*Q1*Q1
      VAL = F1/3.0
      DO 1500 I = 1, L
      AI = I
      F1 = -F1*0.25*Z*Z/(AI*AI+AI)
 1500 VAL = VAL+F1/(2.0*AI+3.0)
      GO TO 1520
 1510 Z1 = 1./Z
      X0 = (((-188.1357*Z1+109.1142)*Z1-23.79333)*Z1+2.050931)*Z1
      X0 = ((X0-0.1730503)*Z1+0.7034845)*Z1-0.064109E-3
      X1 = (((-5.817517*Z1+2.105874)*Z1-.6896196)*Z1+.4952024)*Z1
      X1 = (X1-0.187344E-2)*Z1+0.7979095
      VAL = (1.0-SQRT(Z)*(X1*COS(Z-PI/4.)-X0*SIN(Z-PI/4.)))/(X*X*X)
 1520 RETURN
      END
```

```
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      SUBROUTINE XFORM(N, TR, R5, U, T)
      COMMON/B1/BETA0, BETA1
      COMPLEX BETA0, BETA1, EX, TR
      DIMENSION EX(2), U(10), T(10), TR(2, 2)
      EX(1) = CEXP(-BETA0*U(N-1)*T(N-1)/R5)
      EX(2) = 1.0/EX(1)
      DO 1610 I = 1, 2
      DO 1610 J=1, 2
      K = I+J
      IF(K.EQ.3) GO TO 1600
      TR(I, J) = (BETA1+BETA0)*EX(J)
      GO TO 1610
 1600 TR(I, J) = (BETA1-BETA0)*EX(J)
 1610 CONTINUE
      RETURN
      END
```

```
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0001          SUBROUTINE MATRIX(JUMP, V, TR)
0002          COMPLEX V, Q, TR
0003          DIMENSION Q(2, 2), V(2, 2), TR(2, 2)
0004          IF(JUMP.EQ.1) GO TO 1720
0006          DO 1700 I=1, 2
0007     1700 Q(I, 1) = V(I, 1)
0008          DO 1710 I=1, 2
0009          V(I, 1) = (0.0, 0.0)
0010          DO 1710 J=1, 2
0011     1710 V(I, 1) = V(I, 1)+TR(I, J)*Q(J, 1)
0012     1720 DO 1730 I=1, 2
0013     1730 Q(I, 2) = V(I, 2)
0014          DO 1740 I=1, 2
0015          V(I, 2) = (0.0, 0.0)
0016          DO 1740 J=1, 2
0017     1740 V(I, 2) = V(I, 2)+TR(I, J)*Q(J, 2)
0018          RETURN
0019          END
```

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```
      SUBROUTINE CIRCT(TMAG, PHASE, Q0, T1, T2)
      COMPLEX MUT, DRIVER, PICKUP, Z1, Z2, Z3, Z4, Z5, Z6, Z7
      COMPLEX DENOM, TNUM, VOLT
      COMMON /B2/ R1, R2, R3, R4, L2, L3, L4, L5, L6, N3, N4,
     $    R6, R7, R0, R9, C6, C7, V0, G5, W, F, R5
      COMMON /B3/ MUT, DRIVER, PICKUP, AIR1, AIR2
      DIMENSION MUT(3, 5), DRIVER(3, 5), PICKUP(3, 5)
      DIMENSION TMAG(3, 5), PHASE(3, 5)
      REAL L3, L4, N3, N4, L2, L5, L6
      T1 = N3/((R2-R1)*L3)
      T2 = N4/((R4-R3)*L4)
      Q0 = 6.300475204E-7*F*R5
      Z1 = CMPLX(W*C6*R0, -1.0)
      Z2 = CMPLX(W*C7*R9, -1.0)
      Z3 = CMPLX(0.0, -R0)
      Z4 = CMPLX(0.0, -R9)
      DO 1800 I=1, 3
      DO 1800 J=1, 5
      Z5 = Q0*T1*T2*MUT(I, J)
      Z6 = Q0*T1*T1*(0.0, 1.0)*(DRIVER(I, J)+AIR1)
      Z7 = Q0*T2*T2*(0.0, 1.0)*(PICKUP(I, J)+AIR2)
      DENOM = Z1*Z2*Z5*Z5+(Z1*(Z6+R6)+Z3)*(Z2*(Z7+R7)+Z4)
      TNUM = V0*R9*G5*(0.0, -1.0)*Z5
      VOLT = TNUM/DENOM
      TMAG(I, J)= CABS(VOLT)
 1800 PHASE(I, J) = ATAN2(AIMAG(VOLT), REAL(VOLT))
      RETURN
      END
```

```
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              SUBROUTINE PHASET(A, B, C, V1, O3)
              DIMENSION A(3, 5), B(3, 5), C(3, 5)
              O1 = A(2, 5)*SIN(B(2, 5))-A(2, 1)*SIN(B(2, 1))
              O2 = -(A(2, 5)*COS(B(2, 5))-A(2, 1)*COS(B(2, 1)))
              O3 = ATAN2(O1, O2)
              V1 = A(2, 1)*SIN(O3+B(2, 1))
              DO 1900 I=1, 3
              DO 1900 J=1, 5
         1900 C(I, J) = O3-ATAN2(V1, SQRT(A(I, J)*A(I, J)-V1*V1))+B(I, J)
              RETURN
              END
```

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```
      SUBROUTINE SENS(TH, RAD, TH1)
      DIMENSION TH(3, 5)
      TH9 = TH(1, 1)
      TH0 = TH(1, 1)
      DO 2010 I=2, 5
      IF(TH(1, I).LT.TH9) GO TO 2000
      TH9 = TH(1, I)
 2000 IF(TH(1, I).GT.TH0) GO TO 2010
      TH0 = TH(1, I)
 2010 CONTINUE
      TH1 = (TH(1, 1)+TH(1, 2)+TH(1, 3)+TH(1, 4)+TH(1, 5))/5.0
      TH1 = TH1-(TH(3, 1)+TH(3, 2)+TH(3, 3)+TH(3, 4)+TH(3, 5))/5.
      XLO = TH9-TH0
      PERCT = 100.*XLO/TH1
      DEGR1 = TH1*RAD
      DEGR2 = XLO*RAD
      TYPE 2020, TH1, XLO, PERCT
 2020 FORMAT(' PHASE SHIFT=', 1PE12.5, 2X, 'LIFTOFF='
     $      , E12.5, 2X, '%=', E12.5)
      TYPE 2030, DEGR1, DEGR2
 2030 FORMAT(' DEGREE:', 1PE13.5, 5X, E13.5)
      RETURN
      END
```

```
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           SUBROUTINE GAGER(RES)
           COMMON/B4/G, D1, D2, RLN, T5, N1A, J1, D, E
           PI = 3.1415926536
           IF(J1.EQ.1) GO TO 2120
           N1A = -1
           D3 = 0.95*SQRT((D2-D1)*RLN/T5)
           X2 = 1.0371E-5/(D3*D3)
           Q = 40.0
     2100  G = 40.+10.*(ALOG(X2)-ALOG(.9989+.017*(Q/10.-1.)))/2.30259
           IF(ABS(Q-G).LT.1.E-4) GO TO 2110
           Q = G
           GO TO 2100
     2110  IG = G
           G = IG
     2120  X2 = (.9989+.017*(G/10.-1.))*10.**(G/10.-4.)
           D3 = SQRT(1.0371E-5/X2)
           IF(G.GT.40.) GO TO 2130
           X3 = (.460655*ALOG(D3*1.E3)-.43444)*1.E-3
           GO TO 2140
     2130  X3 = (98.02228*D3+2.56791E-2)*1.E-3
     2140  ID = (RLN/(D3+X3))
           D = ID
           IE = (D2-D1)/(D3+X3)
           E = IE
           IF(N1A.EQ.-1) GO TO 2150
           T5 = D*E
     2150  RES = T5*X2*(D2+D1)*PI/12.0
           RETURN
           END
```

```
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0001          SUBROUTINE CIRCT1(TH1, V1, TH, RAD, SEN)
0002          DIMENSION TH(3, 5), TMAG(3, 5), PHASE(3, 5)
0003          CALL CIRCT(TMAG, PHASE, Q0, T1, T2)
0004          Q1 = 0.0
0005          DO 2200 I=1, 3
0006          DO 2200 J=1, 5
0007          Q2 = TH1-ATAN2(V1, SQRT(TMAG(I, J)**2-V1**2))
         $        +PHASE(I, J)-TH(I, J)
0008          IF(ABS(Q1).GT.ABS(Q2)) GO TO 2200
0010          Q1 = Q2
0011     2200 CONTINUE
0012          Q2NEW = RAD*Q1
0013          Q3 = 100.*Q1/SEN
0014          TYPE 2210, Q1, Q2NEW, Q3
0015     2210 FORMAT('+', 1X, 2(1PE12.5, 2X), 1PE12.5)
0016          RETURN
0017          END
```

```
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0001          SUBROUTINE BESS1(VAL)
0002          COMMON X, Z, Q1, PI
0003          IF(Z.GT.5.0) GO TO 1510
0005          L = 2.0*Z+3.0
0006          F1 = 0.5*Z*Q1*Q1
0007          VAL = F1/3.0
0008          DO 1500 I = 1, L
0009          AI = I
0010          F1 = -F1*0.25*Z*Z/(AI*AI+AI)
0011     1500 VAL = VAL+F1/(2.0*AI+3.0)
0012          GO TO 1520
0013     1510 Z1 = 1./Z
0014          X0 = (((-188.1357*Z1+109.1142)*Z1-23.79333)*Z1+2.050931)*Z1
0015          X0 = ((X0-0.1730503)*Z1+0.7034845)*Z1-0.064109E-3
0016          X1 = (((-5.817517*Z1+2.105874)*Z1-.6896196)*Z1+.4952024)*Z1
0017          X1 = (X1-0.187344E-2)*Z1+0.7979095
0018          VAL = (1.0-SQRT(Z)*(X1*COS(Z-PI/4.)-X0*SIN(Z-PI/4.)))/(X*X)
0019     1520 RETURN
0020          END
```

```
      SUBROUTINE RFCDS1
      COMMON /C2/ Z, R
      IF(Z .GT. 3) GO TO 100
      Z2 = Z**2
      Q1 = (((2.1E-11*Z2-5.38E-9)*Z2+6.757E-7)*Z2-5.48443E-5)*Z2
      Q1 = ((Q1+2.60415E-3)*Z2-6.25E-2)*Z2+.5
      R = Z*Q1
      RETURN
100   Z1 = 1./Z
      Q3 = (((-.14604057*Z1+.27617679)*Z1-.20210391)*Z1+4.61835E-3)*Z1
      Q3 = ((Q3+.14937)*Z1+4.68E-6)*Z1+.79788456
      Q4 = (((-.21262014*Z1+.19397232)*Z1+6.022188E-2)*Z1
     $     -1.7222733E-1)*Z1
      Q4 = ((Q4+5.085E-4)*Z1+.37498836)*Z1-2.35619449+Z
      R = Q3*COS(Q4)/SQRT(Z)
      RETURN
      END
```

EDTRFC

```
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        C..     PROGRAM EDTRFC.FOR
        C..
        C..     ALLOWS INPUT PARAMETERS FOR MULTILAYERED
        C..     REFLECTION COIL PROGRAMS TO BE CHANGED
        C..
        C..     D. T. HAYFORD & CHIP WILSON
        C..     BATTELLE COLUMBUS LABORATORIES  12-19-78
        C..
0001            REAL*4 MATL
0002            LOGICAL*1 IANS, YES
0003            DIMENSION COIL(13), AMP(6), MATL(10, 3), ITITL(20)
0004            DIMENSION VERB(8), VERB1(6), VERB2(14), VERB3(5),
             $      VERB4(7)
0005            DATA VERB/'COIL', 'MATL', 'AMP ', 'EXIT', 5*'EXIT'/
0006            DATA VERB1/'SAVE', 'CHNG', 'LIST', 'HELP', 'RET ', 'EXIT'/
0007            DATA VERB2/'R1  ', 'R2  ', 'R3  ', 'R4  ', 'L2  ', 'L3  ',
             $      'L4  ', 'L5  ', 'L6  ', 'N3  ', 'N4  ', 'RES1', 'RES2', 'NONE'/
0008            DATA VERB3/'T   ', 'MU  ', 'RHO', 'NUM ', 'NONE'/
0009            DATA VERB4/'RES3', 'RES4', 'CAP3', 'CAP4', 'VOUT', 'GAIN', 'NONE'/
0010            DATA YES/'Y'/
0011         10 CALL COMAND(VERB, 8, IFILE, 'ENTER FILE TYPE: ')
0012            GO TO (100, 200, 300, 400) IFILE
        C..
        C..   'COIL'--INPUT COIL PARAMETERS
        C..
0013        100 CALL ATTIN(2, IFILE, 0, ICUR)
        C..     READ THE FILE
0014            READ(2) ITITL, COIL
0015            CALL CLOSE(2)
        C..
        C..     GET NEXT COMMAND
0016        110 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0017            GO TO (120, 130, 140, 150, 160, 400) J
        C..
        C..   'SAVE'--WRITE THE COIL PARAMETERS OT TO DISK
0018        120 CALL ATTOUT(2, IFILE, 0, ICUR)
0019            CALL TITLE(ITITL)
0020            WRITE(2) ITITL, COIL
0021            CALL CLOSE(2)
0022            GO TO 110
        C..
        C..   'CHNG'--CHANGE THE COIL PARAMETERS
0023        130 K = 1
0024            CALL COMAND(VERB2, 14, J, 'ITEM: ')
0025            IF(J .EQ. 14) K = 2
0027            GO TO (135, 110) K
0028        135 TYPE 136, COIL(J)
0029        136 FORMAT(' OLD VALUE: ', 1PE12.5/'$NEW VALUE: ')
0030            ACCEPT 137, COIL(J)
0031        137 FORMAT(F10.0)
0032            GO TO 130
        C..
        C..   'LIST'--LIST PRESENT COIL FILE
0033        140 TYPE 141, ITITL, COIL
```

```
0034      141 FORMAT(1X, 20A2//T10, 'R1 = ', F7.4, T25, 'R2 = ',
            1     F7.4/T10, 'R3 = ', F7.4, T25, 'R4 = ', F7.4/
            2     T10, 'L2 = ', F7.4, T25, 'L3 = ', F7.4/T10, 'L4 = ',
            3     F7.4, T25, 'L5 = ', F7.4/T10, 'L6 = ', F7.4/T10, 'N3 = ',
            4     F7.1, T25, 'N4 = ', F7.1/T8, 'RES1 = ', F7.1, T23,
            5     'RES2 = ', F7.1//)
0035          GO TO 110
        C..
        C..  'HELP'--GIVE A LIST OF VARIABLE NAMES
0036      150 TYPE 151
0037      151 FORMAT(' R1 = DRIVER COIL INNER RADIUS'/
            $     ' R2 = DRIVER COIL OUTER RADIUS'/
            $     ' R3 = PICKUP COIL INNER RADIUS'/
            $     ' R4 = PICKUP COIL OUTER RADIUS'/
            $     ' L2 = LIFTOFF INCREMENT'/
            $     ' L3 = DRIVER COIL LENGTH'/
            $     ' L4 = PICKUP COIL LENGTH'/
            $     ' L5 = PICKUP COIL RECESS'/
            $     ' L6 = MINIMUM LIFTOFF'/
            $     ' N3 = NO. OF TURNS-DRIVER'/
            $     ' N4 = NO. OF TURNS-PICKUP'/
            $     ' RES1 = RESISTANCE OF DRIVER'/
            $     ' RES2 = RESISTANCE OF PICKUP'//)
0038          GO TO 110
        C..
        C..  'RET '--RETURN TO PROGRAM BEGINNING
0039      160 GO TO 10
        C..
        C..  'MATL'--INPUT MATERIAL PARAMETERS
        C..
0040      200 CALL ATTIN(2, IFILE, 0, ICUR)
        C..   READ THE FILE
0041          READ(2) ITITL, NUM, MATL
0042          CALL CLOSE(2)
        C..
        C..   GET THE NEXT COMMAND
0043      210 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0044          GO TO (220, 230, 240, 250, 160, 400) J
        C..
        C..  'SAVE'--WRITE MATERIAL PARAMETERS OUT TO DISK
0045      220 CALL ATTOUT(2, IFILE, 0, ICUR)
0046          CALL TITLE(ITITL)
0047          WRITE(2) ITITL, NUM, MATL
0048          CALL CLOSE(2)
0049          GO TO 210
        C..
        C..  'CHNG'--CHANGE MATERIAL PARAMETERS
0050      230 CALL COMAND(VERB3, 5, J, 'ITEM: ')
0051          GO TO (231, 231, 231, 235, 210) J
0052      231 TYPE 232
0053      232 FORMAT('$LAYER NO.: ')
0054          ACCEPT 233, K
0055      233 FORMAT(I2)
0056          K = K+1
```

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FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:04:30                 PAGE 003

0057          IF(K .LT. 2 .OR. K .GT. NUM-1) GO TO 231
0059          TYPE 234, MATL(K, J)
0060      234 FORMAT(' OLD VALUE: ', 1PE12.5/'$NEW VALUE: ')
0061          ACCEPT 137, MATL(K, J)
0062          GO TO 230
0063      235 TYPE 236, NUM - 2
0064      236 FORMAT(' OLD VALUE: ', I2/'$NEW VALUE: ')
0065          ACCEPT 233, NUMDUM
0066          NUMDUM = NUMDUM + 2
0067          IF(NUMDUM .LT. 1 .OR. NUMDUM .GT. 10) GO TO 235
0069          NUM = NUMDUM
0070          IF (NUM .EQ. 10) GO TO 230
0072          DO 237 I=1, 3
0073          DO 237 J=NUM+1, 10
0074      237 MATL(J, I) = 0.
0075          MATL(1, 1) = 1.E10
0076          MATL(1, 2) = 1.
0077          MATL(1, 3) = 1.E10
0078          MATL(NUM, 1) = 1.
0079          MATL(NUM, 2) = 1.
0080          MATL(NUM, 3) = 1.E10
0081          GO TO 230
        C..
        C..   'LIST'--LIST PRESENT MATERIAL FILE
0082      240 TYPE 241, ITITL, NUM, (J,( MATL(J, I), I=1, 3), J=1, 10)
0083      241 FORMAT(1X, 20A2//' NO. OF LAYERS: ', I2//
             $     T2, 'LAYER', T20, 'THICKNESS', T44, 'MU', T64, 'RHO'//
             $     10(T4, I2, T20, 1PE10.4, T40, E10.4, T60, E10.4/))
0084          GO TO 210
        C..
        C..   'HELP'--GIVE LIST OF INPUT PARAMETERS
0085      250 TYPE 251
0086      251 FORMAT(' LAYERS ARE NUMBERED FROM ONE TO 'NUM+2', STARTING'/
             $      ' FROM THE BOTTOM.  LAYER 1 IS ALWAYS AIR, WITH AN INFINITE'/
             $      ' THICKNESS, AND LAYER'NUM+2' IS AIR WITH A THICHNESS OF 1.'//
             $     'THE VARIABLES TO BE ENTERED ARE:'//
             $      ' T = THICKNESS (IN INCHES)'/
             $      ' MU = RELATIVE PERMEABILITY'/
             $      ' RHO = RESISTIVITY (IN MU-OHM-CM)')
0087          GO TO 210
        C..
        C..   'AMP '--INPUT AMPLIFIER PARAMETERS
        C..
0088      300 CALL ATTIN(2, IFILE, 0, ICUR)
        C..   READ THE FILE
0089          READ(2) ITITL, AMP
0090          CALL CLOSE(2)
        C..   GET NEXT COMMAND
0091      310 CALL COMAND(VERB1, 6, J, 'COMMAND: ')
0092          GO TO (320, 330, 340, 350, 160, 400) J
        C..
        C..   'SAVE'--WRITE AMPLIFIER PARAMETERS OUT TO DISK
0093      320 CALL ATTOUT(2, IFILE, 0, ICUR)
0094          CALL TITLE(ITITL)
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:04:30                 PAGE 004

0095          WRITE(2) ITITL, AMP
0096          CALL CLOSE(2)
0097          GO TO 310
        C..
        C..   'CHNG'--CHANGE AMPLIFIER PARAMETERS
0098      330 K = 1
0099          CALL COMAND(VERB4, 7, J, 'ITEM: ')
0100          IF (J .EQ. 7) K = 2
0102          GO TO (331, 310) K
0103      331 TYPE 234, AMP(J)
0104          ACCEPT 137, AMP(J)
0105          GO TO 330
        C..
        C..   'LIST'--LIST PRESENT AMPLIFIER FILE
0106      340 TYPE 341, ITITL, AMP
0107      341 FORMAT(1X, 20A2//T10, 'RES3 = ', 1PE12.5/
             $     T10, 'RES4 = ', E12.5/T10, 'CAP3 = ', E12.5/
             $     T10, 'CAP4 = ', E12.5/T10, 'VOUT = ', E12.5/
             $     T10, 'GAIN = ', E12.5//)
0108          GO TO 310
        C..
        C..   'HELP'--GIVE LIST OF VARIABLE NAMES
0109      350 TYPE 351
0110      351 FORMAT(' RES3 = DRIVER AMPLIFIER SERIES RES. (OHMS)'/
             $     ' RES4 = PICKUP AMPLIFIER SERIES RES. (OHMS)'/
             $     ' CAP3 = DRIVER CIRCUIT SHUNT CAP. (FARADS)'/
             $     ' CAP4 = PICKUP CIRCUIT SHUNT CAP. (FARADS)'/
             $     ' VOUT = DRIVER OUTPUT VOLTAGE (VOLTS)'/
             $     ' GAIN = PICKUP AMPLIFIER GAIN'//)
0111          GO TO 310
        C..
        C..   'EXIT'--EXIT THE PROGRAM
        C..
0112      400 TYPE 401
0113      401 FORMAT('$ARE YOU SURE (Y/N)? ')
0114          ACCEPT 402, IANS
0115      402 FORMAT(A1)
0116          IF(IANS .EQ. YES) GO TO 410
0118          GO TO (110, 210, 310, 10) IFILE
0119      410 CALL EXIT
0120          END
```

# UTILITY SUBROUTINES

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:01:12                 PAGE 001

0001          SUBROUTINE ATTIN(LUN, NENTRY, IFLAG, IOPEN)
        C..
        C..    THIS SUBROUTINE ATTACHES A FILE FOR INPUT BY
        C..   CHECKING THE FILE NAME DIRECTORY FOR THE FILENAME
        C..   AND DEFAULT SEQUENCE NUMBERS. EITHER THE DEFAULT
        C..   WILL BE USED OR THE OPERATOR WILL BE PROMPTED FOR
        C..   ONE.
        C..
        C..   INPUT PARAMETERS:
        C..
        C..   LUN -- LOGICAL UNIT NUMBER TO BE USED FOR
        C..         THE FILE TO BE ATTACHED.
        C..
        C..   NENTRY -- NUMBER FOR THE DIRECTORY ENTRY
        C..         TO BE OPENED.
        C..
        C..   IFLAG -- =0  PROMPT OPERATOR FOR SEQUENCE NO.
        C..            =-1  USE DEFAULT VALUE
        C..            .GT. 0  USE IFLAG AS CURRENT FILE NUMBER
        C..
        C..   OUTPUT PARAMETERS
        C..
        C..   IOPEN -- SET EQUAL TO THE SEQUENCE NO.
        C..            OF THE FILE OPENED.
        C..
0002          LOGICAL*1 STRING(42)
0003          COMMON/FILNAM/ LUNUM, N, STRING, ICUR, INEXT, IAV
0004          LUNUM = LUN
0005          N = NENTRY
        C..
        C..   ATTACH THE FILE NAME DIRECTORY.
        C..
0006       10 CALL DIROPN
0007          I = IFLAG
0008          IF(IFLAG) 100, 35, 50
        C..
        C..   USE CURRENT FILE SEQUENCE NUMBER?
        C..
0009     35   TYPE 40, (STRING(I), I=12, 14), ICUR
0010     40   FORMAT('$OPEN ', 3A1, ' FILE #', I3, ' ? ')
0011          READ(5, 30, ERR=35) I
0012     30   FORMAT(I10)
0013          IF(I .LT. 0  .OR.  I .GT. 999) GO TO 35
0015          IF(I .EQ. 0) I = ICUR
0017     50   ICUR = I
0018          CALL DIRCLO
0019          GO TO 140
0020    100   CALL CLOSE(LUNUM)
        C..
        C..   CHECK FOR EXISTENCE OF FILE
        C..
0021      140 IF(IEXIST(STRING) .GT. 0) GO TO 150
0023          TYPE 65, (STRING(I), I=12, 14), ICUR
0024       65 FORMAT(' ', 3A1, ' FILE #', I3, ' NOT FOUND.')
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:01:12                      PAGE 002

0025           GO TO 10
         C..
         C..   OPEN THE FILE.
         C..
0026      150  IF(IFLAG .NE. 0) TYPE 60, (STRING(I), I=12, 14), ICUR
0028       60  FORMAT(' ', 3A1, ' FILE #', I3, ' OPENED.')
0029           CALL ASSIGN(LUNUM, STRING, 14, 'OLD')
0030           IOPEN = ICUR
0031           RETURN
0032           END
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:01:42                PAGE 001

0001            SUBROUTINE ATTOUT(LUN, NENTRY, IFLAG, INEW)
          C..
          C..    THIS SUBROUTINE ATTACHES A FILE FOR OUTPUT
          C..   BY CHECKING THE FILE NAME DIRECTORY FOR THE
          C..   FILENAME AND THE NEXT AVAILABLE SEQUENCE
          C..   NUMBER; THEN, EITHER THE DEFAULT NUMBER WILL
          C..   BE USED OR THE OPERATOR WILL BE PROMPTED FOR
          C..   ONE.
          C..
          C..   INPUT:
          C..
          C..   LUN -- LOGICAL UNIT NUMBER FOR THE FILE
          C..          TO BE ATTACHED.
          C..
          C..   NENTRY -- THE DIRECTORY TO BE OPENED.
          C..
          C..   IFLAG -- =0  PROMPT OPERATOR FOR SEQ. NO.
          C..              =-1  USE NEXT AVAILABLE SEQ. NO.
          C..             .GT. 0  USE IFLAG AS FILE SEQ. NO.
          C..   OUTPUT:
          C..
          C..   INEW -- EQUAL TO THE SEQUENCE NO. OF FILE OPENED.
          C..
0002            LOGICAL*1 STRING(42)
0003            COMMON/FILNAM/ LUNUM, N, STRING, ICUR, INEXT, IAV
0004            LUNUM = LUN
0005            N = NENTRY
          C..
          C..   ATTACH THE FILE NAME DIRECTORY.
          C..
0006            CALL DIROPN
0007            I = IFLAG
0008            IF(IFLAG) 100, 35, 50
          C..
          C..   USE NEXT SEQUENCE NUMBER?
          C..
0009       35   TYPE 40, (STRING(I), I=12, 14), INEXT
0010       40   FORMAT('$SAVE AS ', 3A1, ' FILE #', I3, ' ? ')
0011            READ(5, 30, ERR=35) I
0012       30   FORMAT(I10)
0013            IF(I .LT. 0  .OR.  I .GT. 999) GO TO 35
0015       50   ICUR = I
0016            IF((I .NE. 0) .AND. (I .NE. INEXT)) GO TO 140
          C..
          C..   USE NEXT AVAILABLE SEQUENCE NUMBER.
          C..
0018      100   ICUR = INEXT
0019            INEXT = INEXT + 1
          C..
          C..   CHECK FOR EXISTENCE OF FILE
          C..
0020      140   CALL DIRCLO
0021            IF(IEXIST(STRING) .GE. 0) TYPE 65, (STRING(I), I=12, 14), ICUR
0023       65   FORMAT(' OLD ', 3A1, ' FILE #', I3, 'DELETED.')
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:01:42                          PAGE 002
0024              IF(IFLAG .NE. 0) TYPE 60, (STRING(I), I=12, 14), ICUR
0026        60    FORMAT(' SAVE AS ', 3A1, ' FILE #', I3, '.')
0027              CALL ASSIGN(LUN, STRING, 14, 'NEW')
0028              INEW = ICUR
0029              RETURN
0030              END
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:02:10                PAGE 001

0001            SUBROUTINE DIROPN
          C..
          C..    THIS SUBROUTINE ATTACHES THE FILE NAME DIRECTORY,
          C..   LOOKS UP THE REQUESTED ENTRY, AND REPORTS THE
          C..   CURRENT AND NEXT SEQUENCE NUMBERS.
          C..
          C..   INPUT:
          C..
          C..   LUNUM -- LOGICAL UNIT NUMBER.
          C..
          C..   NENTRY -- DIRECTORY ENTRY TO BE OPENED.
          C..
          C..   OUTPUT:
          C..
          C..   STRING -- ARRAY CONTAINING THE FILE NAME.
          C..
          C..   ICUR -- CURRENT SEQUENCE NUMBER.
          C..
          C..   INEXT -- NEXT SEQUENCE NUMBER.
          C..
0002            LOGICAL*1 STRING(42), DUM1(3), DUM2(3)
          C..
0003            COMMON/FILNAM/ LUNUM, NENTRY, STRING, ICUR, INEXT, IAV
          C..
0004            EQUIVALENCE (DUM1(1), STRING(8)), (DUM2(1), STRING(16))
          C..
          C..
          C..   ATTACH THE FILE NAME DIRECTORY.
          C..
0005            CALL ASSIGN(LUNUM, 'DIR:RFCRFC.DIR', 14)
0006            DEFINE FILE LUNUM(4, 21, U, IAV)
0007            IAV = NENTRY + 1
          C..
          C..   READ IN THE REQUESTED ENTRY.
          C..
0008            READ(LUNUM'IAV) STRING
          C..
          C..   DETERMINE CURRENT AND NEXT AVAILABLE SEQ. NO.
          C..
0009            DECODE (3, 30, DUM1) ICUR
0010            DECODE (3, 30, DUM2) INEXT
0011      30    FORMAT(I3)
0012            RETURN
0013            END
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:02:30               PAGE 001

0001          SUBROUTINE DIRCLO
        C..
        C..    THIS SUBROUTINE UPDATES AND CLOSES THE FILE
        C..   NAME DIRECTORY.
        C..
        C..   INPUT:
        C..
        C..   LUNUM -- LOGICAL UNIT NUMBER.
        C..
        C..   NENTRY -- DIRECTORY ENTRY TO BE UPDATED.
        C..
        C..   STRING -- ARRAY CONTAINING THE FILENAME.
        C..
        C..   ICUR -- CURRENT SEQUENCE NUMBER.
        C..
0002          LOGICAL*1 STRING(42), DUM1(3), DUM2(3), DUM3, DUM4
        C..
0003          COMMON/FILNAM/ LUNUM, NENTRY, STRING, ICUR, INEXT, IAV
        C..
0004          EQUIVALENCE (DUM1(1), STRING(8)), (DUM2(1), STRING(16))
        C..
        C..
        C..   ENCODE ICUR AND INEXT INTO STRING
        C..
        C..
0005          DUM3 = STRING(11)
0006          ENCODE (3, 30, DUM1) ICUR
0007          STRING(11) = DUM3
        C..
0008          DUM3 = STRING(19)
0009          ENCODE (3, 30, DUM2) INEXT
0010          STRING(19) = DUM3
        C..
0011     30   FORMAT(I3)
        C..
        C..   CONVERT BLANKS TO ZEROS.
        C..
0012          IF(STRING(8)  .EQ. '040) STRING(8)  = '060
0014          IF(STRING(9)  .EQ. '040) STRING(9)  = '060
0016          IF(STRING(16) .EQ. '040) STRING(16) = '060
0018          IF(STRING(17) .EQ. '040) STRING(17) = '060
0020          IAV = NENTRY + 1
        C..
        C..   UPDATE DIRECTORY ENTRY AND CLOSE IT.
        C..
0021          WRITE(LUNUM'IAV) STRING
0022          CALL CLOSE(LUNUM)
0023          RETURN
0024          END
```

```
0001          SUBROUTINE TITLE( ITITLE)
        C..
        C..   PROGRAMMED BY CHIP WILSON.
        C..
        C..   THIS SUBROUTINE LISTS THE 40 CHARACTER TITLE CONTATNED IN
        C..   ARRAY ITITLE, ASKS THE OPERATOR IF HE WANTS TO CHANGE IT,
        C..   AND RETURNS WITH EITHER THE OLD TITLE OR A NEW TITLE AS
        C..   ENTERED BY THE OPERATOR.
        C..
0002          LOGICAL*1 ITITLE(40), ANS
        C..
0003          TYPE 200, ITITLE
0004    200   FORMAT(' PRESENT TITLE:  >', 40A1, '<', /, '$NEW TITLE (Y/N)? ')
0005          ACCEPT 210, ANS
0006    210   FORMAT( 40A1)
0007          IF( ANS .NE. "131) RETURN
0009          DO 300 J=1, 40
0010    300   ITITLE(J) = "040
0011          CALL MSGOUT('ENTER NEW TITLE: ')
0012          ACCEPT 210, ITITLE
0013          RETURN
0014          END
```

```
FORTRAN IV      V01C-03G   FRI 19-OCT-79 10:03:08                 PAGE 001

              SUBROUTINE COMAND(ARRAY, ISIZE, MATCH, PROMPT)
        C..
        C..   PROGRAMMED BY CHIP WILSON.
        C..
        C..    A FOUR CHARACTER COMMAND IS INPUT FROM THE
        C..   KEYBOARD AND A SEARCH IS MADE FOR A MATCH.
        C..    A NONAMBIGUOUS ABREVIATION IS CONSIDERED A
        C..   VALID MATCH.
        C..   IF NO MATCH IS FOUND, ALL COMMANDS ARE LISTED OUT
        C..   AND THE ROUTINE WAITS FOR ANOTHER INPUT.
        C..
        C..   INPUT -
        C..     ARRAY -- ARRAY OF COMMANDS TO BE CHECKED.
        C..     ISIZE -- NUMBER OF COMMANDS TO BE CHECKED.
        C..     PROMPT -- CHARACTER STRING CONTAINING A PROMPTING
        C..               MESSAGE TERMINATED BY A NULL.
        C..
        C..   OUTPUT -
        C..     MATCH -- ARRAY SUBSCRIPT WHERE MATCH OCCURED.
        C..
              LOGICAL*1 PROMPT(1), LTRY(4), REPLY(4)
              EQUIVALENCE (TRY, LTRY(1)), (ANSWER, REPLY(1))
              DIMENSION ARRAY(1)
            3 DO 50 J=1,40
              IF(PROMPT(J) .EQ. 0) GO TO 5
           50 CONTINUE
            5 TYPE 4, (PROMPT(I),I=1,J)
            4 FORMAT(/, '$', 40A1)
              READ(5, 110, ERR=3) ANSWER
          110 FORMAT(A4)
              IFIND = 0
              LETRS = 0
              DO 10 K=1, ISIZE
              TRY = ARRAY(K)
              DO 9 J=1, 4
              IF(REPLY(J) .NE. LTRY(J)) GO TO 20
            9 CONTINUE
           20 IF(J-1 - LETRS) 10,22,21
           21 IFIND = 0
              LETRS = J-1
           22 IFIND = IFIND + 1
              MATCH = K
           10 CONTINUE
              IF(IFIND.EQ.1.AND.(LETRS.EQ.4 .OR. REPLY(LETRS+1).EQ."040)) RETURN
              TYPE 210, (ARRAY(I), I = 1, ISIZE)
          210 FORMAT ('+', 4( 10(A4:, ', ')/, ' '))
              GO TO 3
              END
```

```
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0001            FUNCTION IEXIST(FNAME)
          C..
          C..   THIS FUNCTION PERFORMS A DIRECTORY LOOK UP
          C..   TO CHECK FOR THE EXISTENCE OF A FILE.
          C..
          C..   IEXIST = -1  ERROR.
          C..         = -2  FILE NOT FOUND.
          C..         .GE. 0  FILE FOUND.  IEXIST = NO. OF BLOCKS IN FILE.
          C..
          C..   FNAME = A 14-CHARACTER LOGICAL ARRAY CONTAINING THE FILE NAME
          C..          IN ASCII.  E.G. DEV:FLNAME.EXT
          C..
0002            INTEGER RAD50(4)
0003            LOGICAL*1 FNAME(1)
          C..
          C..   CONVERT FILENAME TO RADIX 50 FORMAT
0004            CALL IRAD50(3, FNAME(1), RAD50(1))
0005            CALL IRAD50(6, FNAME(5), RAD50(2))
0006            CALL IRAD50(3, FNAME(12), RAD50(4))
0007            IEXIST = -1
0008            ICHAN = IGETC()
0009            IF(ICHAN .LT. 0) RETURN
0011            IEXIST = LOOKUP(ICHAN, RAD50)
0012            CALL CLOSEC(ICHAN)
0013            CALL IFREEC(ICHAN)
0014            RETURN
0015            END
```

```
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0001          SUBROUTINE MSGOUT(MSG)
        C..
        C..   PROGRAMMED BY CHIP WILSON
        C..
        C..   THIS ROUTINE SENDS AN ASCII MESSAGE OUT TO THE
        C..   TERMINAL.  THE LOGICAL*1 STRING, MSG, MUST BE
        C..   TERMINATED BY A NULL BYTE.
        C..
0002          LOGICAL*1 MSG(1)
        C..
0003          DO 10 J=1, 80
0004          IF ( MSG(J) .EQ. 0 ) RETURN
0006     5    IF ( ITTOUR(MSG(J)) .EQ. 1 ) GO TO 5
0008    10    CONTINUE
0009          RETURN
0010          END
```

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